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Thin-film solar

Bright prospects and shady claims

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Martin Bellamy

Martin Bellamy operates as an independent photovoltaics specialist providing training, product design and strategic business advice to organisations ranging from African governments to renewable-energy businesses and photovoltaics manufacturers.

He has more than 20 years of engineering experience, including a decade working directly within the photovoltaics industry. Bellamy is also the originator of 11 patents related to thin-film photovoltaics technologies.

He holds an honours degree in engineering physics and is chartered as a physicist, engineer and scientist.

Foreword

> It is not too much to expect that our children will enjoy in their homes electrical energy too cheap to meter.

So said Lewis Strauss, Chairman of the US Atomic Energy Commission, in 1954, citing impending advances in nuclear power. Strauss's words have proven somewhat optimistic, with electricity prices continuing their slow, inexorable march upwards since then. Given this failure to deliver, it's no surprise that boffins promising electricity from the sun for free have been greeted with a great degree of scepticism. That is, until now.

The cost of generating electricity from the sun has dropped nearly 90% since the early 1990s and is closing in on retail electricity prices. However, the underlying technology powering more than 90% of these panels has not changed since Elvis first hit the music scene. At the same time, processing power built upon the same basic semiconductor technology has advanced from calculators the size of a room costing millions of dollars to cheap computers the size of calculators. If solar technology had been keeping pace it would be free by now.

Over the past five years, tremendous growth in venture capital funding for new energy technology has given birth to a raft of new next-generation thin-film solar technologies. Each promise to leap-frog existing functionality and cost, with the most ambitious claiming to be 'solar paint' that can generate electricity at much lower cost than fossil fuels.

Success would see some of these thin-film solar technologies displace not only existing solar panels, but traditional power sources as well. So far, the incumbents haven't had much to worry about. The leap from concept to laboratory to commercial production has proven tough. Target production dates seem to be forever receding into the future, even for the less ambitious new technologies.

There have been a few exceptions, most notably First Solar, which enjoys an indisputable cost advantage in the solar space and a valuation multiple to reflect that. Where is "Second Solar"? There is no shortage of qualified candidates (gurus and Nobel Prize winners included), but investors face a tough job making sense of the competing claims and promises.

Our author has first-hand experience bringing a new thin-film solar technology to market, and with this report we aim to help you understand the many failures of the past - and the ones yet to come - and help suss out which technologies just might make it. Electricity may never be too cheap to meter, but solar will alter the energy landscape in ways that few would imagine, and sooner than most expect.

Charles Yonts
Head of Solar Research

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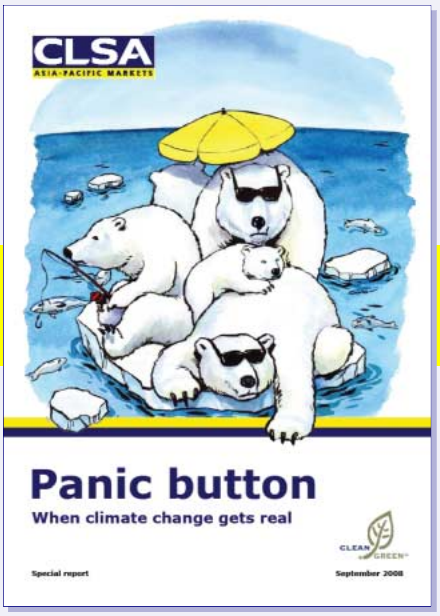
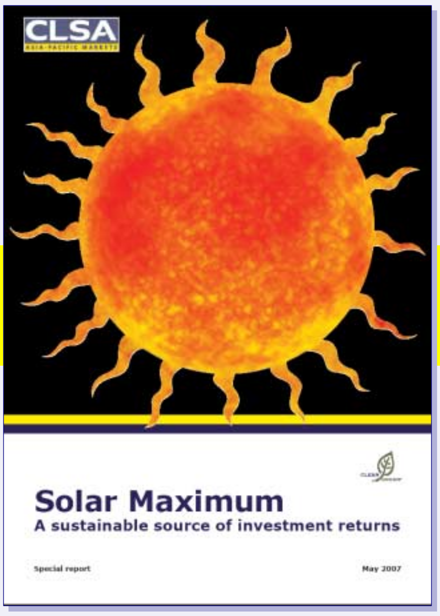




Thin-film solar

Thin-film solar is fast approaching a turning point

Holding the promise to personalise energy, thin-film solar photovoltaics technology is set to reinvigorate the industry; assuming of course that developers can overcome the current roadblocks. Harvesting electricity directly from the sun is both "greener" and cheaper than traditional energy sources, and is set to become the ubiquitous solution in developing countries. Growth is accelerating and we are fast approaching a turning point, with the manufacturers tailoring industry dynamics to favour their interests.

Thin-film has all the qualities of existing PV, with added benefits

Photovoltaics (PV) equipment employs no moving parts, operates silently, generates no emissions, requires little maintenance, is modular in design and requires no fuel besides daylight. On top of this, *thin-film* PV - the deposition of a thin active layer directly onto the (ultimately flexible) substrate - can achieve phenomenal growth using minimal raw materials with low embodied energy and a reduced environmental impact. Currently, crystalline silicon dominates the market with a 90% share. However, thin-film is set to account for anywhere from 10% to 60% of PV production within five years.

Factors driving solar industry

We see several key factors propelling the solar industry in general. First, distributed generation closer to end users, especially with accompanying storage, can allow greater energy ownership and help utilities by reducing peak-capacity requirements. Second, energy-efficiency measures in the home and for off-grid applications increase the value of a given PV capacity. Finally, government policy is driving the uptake of PV in homes and businesses alike, while carbon offsetting could also be an important driver. To date, a history of overpromising and underdelivering has held the industry back, however.

Organic PV the Holy Grail

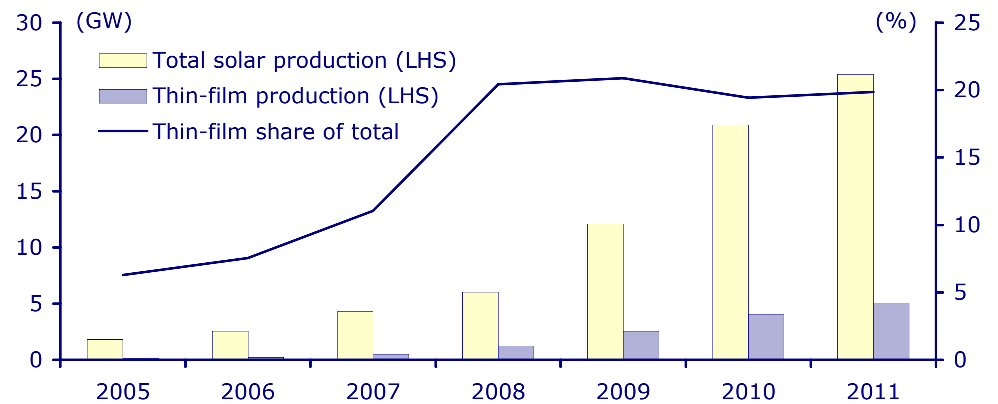
The Holy Grail is organic PV printed on plastics, which can be incorporated into everything from buildings and tents to clothing and bags. The three major thin-film technologies - amorphous silicon, cadmium telluride and copper indium selenium - have yet to reach their potential because they do not combine low cost with reasonable efficiency, high volume and versatile electrical formats.

Thin-film can personalise energy

We see opportunities for thin-film in the small module market; the off-grid market, where crystalline simply cannot deliver on customer requirements; and in the developing world, delivering off-grid electrification. Crystalline PV is likely to remain dominant for at least the next five years, but ultimately, thin-film will personalise energy in the same way the mobile phone has personalised communications.

Thin-film represents only 10% of global production but will steadily increase

Thin-film's share of the total solar market



Source: CLSA Asia-Pacific Markets

Where we stand today

Thin-film overcomes the issues that have held PV back for so many years

Solar photovoltaics - the direct conversion of light into electricity - is key to a clean, secure and sustainable energy future. Whereas PV is expensive, especially when compared to grid electricity, limiting industry growth over the past 30 years, thin-film formats promise lower costs, higher volumes, lower raw material usage, lower embodied energy and reduced environmental impact. Indeed, this technology has the potential to revolutionise the global energy market.

All PV technologies share the same basic attributes: solid-state/no moving parts; silent in operation; no emissions; very low maintenance, modular; and no fuel requirement, besides daylight.

Why PV is fundamental to our energy future

While a number of sustainable energy solutions are now in widespread use, we have identified several key reasons why PV is fundamental to our energy future:

- Urban deployment: Can be widely deployed in urban and rural areas alike.
- Predictability: Sunlight energy varies little regionally (unlike wind).
- Scalability: From utility scale to consumer equipment (calculators, etc).
- Can be personalised: For an individual, their transport and their home.
- It is truly clean: Minimal cradle-to-grave environmental impact.

The advent of thin-film

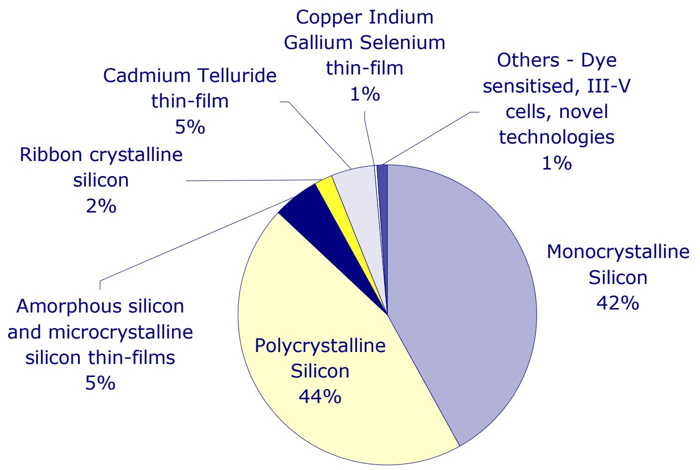
Over 20 years of R&D and thin-film is still only 10% of the market

Thin-film was first promoted in the 1980s with the arrival of the microelectronics industry, though this initial impact did not last. Despite significant investment since the mid-1990s, particularly in amorphous silicon, the technology only now represents a noticeable proportion of the market.

Thin-film technologies accounted for just over 10%

Figure 1

PV market by different formats, 2007



Source: Author

Production capacity figures are not exact

For the past decade, production figures have been derived from supplier-stated output. Due to huge competition in the market (for sales, brand and investment) figures cannot always be taken as exact[1]. Historical production figures are not accurate for a number of reasons. The industry was segmented with many modules being assembled by third parties in the 1980s and actual peak watt figures for the cells varied widely.

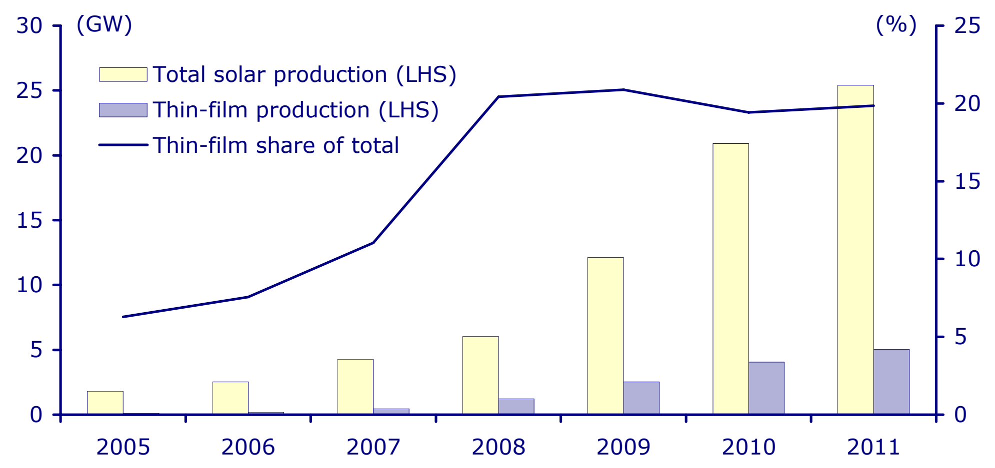
Less than 30 megawatts peak (MWp) of PV was produced and installed in 1994. In 2007 the figure was nearly 4GWp.

Thin-film is set to grow as emerging technologies of the past decade are now commercially competitive. Many formats are already in pilot production (1-2MWp/year) though the transfer to high-volume production (ie, more than 10MWp) can be tricky, as we explain in a later section.

Thin-film's share of the solar market could double from 2007 to 2009

Figure 2

Thin-film's share of the total solar market



Source: CLSA Asia-Pacific Markets

Too many failed promises making predictions more realistic

Predictions for thin-film in the near future are modest. The market has repeatedly been let down after producers have failed to deliver on promises of efficient product at low cost and/or high volume.

Big opportunities are being overlooked

However, thin-film does not need to depend on efficiency and cost, which, while essential for grid-connect applications, are not for off-grid and consumer products. These PV market opportunities - some existing, some in their infancy - are enormous with two billion potential users and turnover easily in excess of US$50bn. To realise this potential products must provide real solutions to end users while delivering the inherent benefits of PV.

The main PV technology groups

There are a number of subsets to these technologies, but we present the major groups from a commercial application perspective in the table below.

[1] For example Sharp reported to Photon International that in 2007 it produced 21MWp of micro-morph thin-film modules at its Katsuragi plant. In November it announced a planned increased production from 15MWp to 160MWp.

Figure 3

Primary PV technology groups

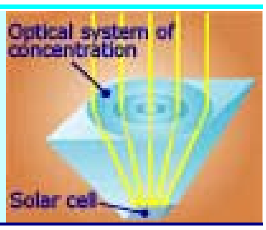
	Space	Crystalline	Concentrator	Thin-film (glass)	Thin-film (flexible)
Example of technology					
Module efficiency	>30% under concentrated light	13-21% (including non-standard formats)	>30% under concentrated light	4-12% (over a range of technologies)	3-8% (over a range of technologies)
Market share, 2007	na	89.6%	<0.1%	10.3% (of which flexible <1%)	
Production cost[2]	>US$10/Wp equivalent	US$2.5-3/Wp	US$3.5-5/Wp	US$1.5-4/Wp	US$4 to >US$10/Wp
Commercial history	First commercial use of PV in 1950s	First commercial modules early 1980s	Emerging in volume mid/late 2000s	Commercial modules early 1990s (Silicon)	Commercial modules late 1990s (silicon)
Pros	High efficiency, long life, resilient	Mature and well established. High (relative) efficiency	Low (expensive) material use. Potential for low cost systems	Low material use ($1/100^{th}$ that of some crystalline) cost, automated production	Rugged, light weight, thin, versatile
Cons	High cost, specialised production	Production cost and time limitations (compared to thin-film)	Need direct sunlight and tracking systems	Low efficiency, potential shortage of raw materials	Some formats still unproven at volume, low efficiency, higher cost
Typical applications	Satellites, space station	All terrestrial applications except concentrator	Utility-scale plants, buildings, ground mounted energy	Huge range from calculators to large buildings	Building integration, portable chargers, leisure and consumer goods
Primary materials	III-V elements: gallium, arsenic, germanium, indium and phosphorus	Silicon	III-V elements: gallium, arsenic, germanium, indium and phosphorus	Silicon, cadmium, indium, gallium, selenium, ruthenium and others	
Comments	Specialist suppliers. R&D influences concentrator systems	Dominates the market	Significant recent development due to silicon shortage	Huge potential to revolutionise energy on a personal and global level	

Source: Author

Focus light onto a small area of photovoltaic material

Concentrator systems[3]

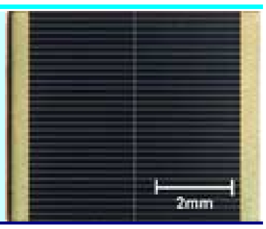
These work by focusing light onto a small area of expensive photovoltaic material using a relatively cheap optical concentrator (such as a Fresnel lens), thus minimising the quantity of PV cells required. The two main drawbacks are that these systems cannot make use of diffuse sunlight and must always be directed towards the sun with a tracking system. These are aimed at very large system applications, though they presently cost more than alternatives.



Only used in concentrating PV systems and in space

III-V PV cells

PV cells used in concentrator applications are typically III-V group compound semiconductors that can have efficiencies of over 30%; higher in the laboratory. Due to the significant material and manufacturing costs, however, they are only used in concentrating PV systems and in space.



Source: Author

[2] Most competitive product costs - large capacity, high volume modules

[3] Different from 'Concentrating Solar Power systems' which employ mirrors to focus light and heat onto thermal conductors to produce steam for turbines.

Crystalline silicon

Crystalline represents 90% of the market

Mono-crystalline (single crystal structure), and poly/multi-crystalline (lattice structure), account for around 90% of the commercial market. It is therefore the benchmark by which all other technologies are assessed.

Figure 4

Overview of crystalline silicon module production

Raw silicon ingot

Crystalline cells are produced from silica, an abundant raw material, though purity requirements make the production process complicated, time consuming and relatively expensive.

The ingots are formed by melting and solidifying silicon using a variety of techniques.

To optimise costs, as large an ingot as is possible (cross sectional area) with the highest purity is desired. However, there are scientific, process and physical limitations constantly challenging producers.

Monocrystalline

Polycrystalline

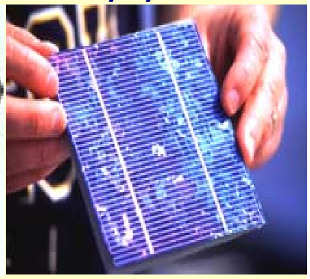
Cells

PV cells are produced by cutting slices, or wafers, of silicon from an ingot and treating the wafers to make the light sensitive cells. Ideally, cells would be cut as thin as possible with minimal waste from the cut, which can be up to a half of the ingot. However, the thinner the cell, the more risk of breakage and the higher the requirements for handling and process equipment.

Production of silicon ingots and the manufacturing of PV cells from them require significant capital investment, which present limitations for the growth of the PV industry.

Monocrystalline

Polycrystalline



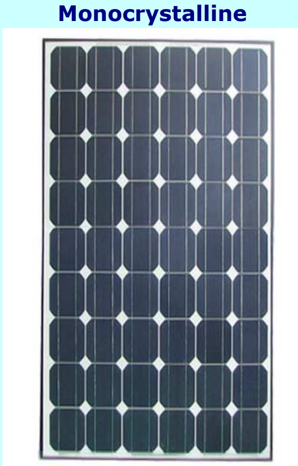
Modules

PV cells are thin, very fragile and must be connected in a series to produce a useable voltage. Although there are variations in crystalline PV module construction, the vast majority of commercial products exhibit common features:

- A glass front to allow light through and protect the cell;
- Multiple cells wired in series;
- A rear encapsulate sheet for environmental protection;
- A rear electrical junction box for external connections; and
- A metal frame for strength and mounting.

Modules are reliable and weatherproof. However, to achieve this, the module materials and process, which contribute 20-35% of the overall cost, contain a lot of embedded energy and this is a primary automation challenge (even at present wafer thicknesses).

Monocrystalline



Polycrystalline

Source: Author

It's not ideal, but it works

Although in many ways not the ideal material for solar cells, crystalline silicon is widely available, well understood and can leverage the same technology developed for the electronics industry. Its cost, reliability, performance, volume capacity, embodied energy and environmental impact are all well understood and undergoing continuous advancement.

Ribbon silicon

To reduce the high silicon wastage from sawing and increase material utilisation several ribbon-cell processes have been developed.

Figure 5

Ribbon silicon: The manufacturing process

Films of silicon are pulled out of the silicon melt using wires. The films are already the thickness of the final wafer.
The film is cut by laser to produce individual wafers. These are processed in the same way as traditional crystalline cells to form modules.
Modern 'standard' cells are around 0.2mm thick but 40% of the original silicon ingot may have become sawdust (which can be recycled). Ribbon cells are less than 0.3mm with the hope of reaching 0.1mm. The cost of the silicon feedstock represents a significant percentage of the finished module cost. The value varies between manufacturers and fluctuates over time, though a figure of 50-80% is representative.

Source: Author

Reduced silicon wastage offsets slightly lower efficiencies

Very few novel production methods have made it to market

Evergreen Solar uses the method described above. RWE Schott Solar uses an edge-defined film-fed growth (EFG) process that involves an octagonal pulling device. GE Energy's (formerly AstroPower) APEX cells are polycrystalline thin-film solar cells on a cost-efficient substrate. APEX cells were the first to be produced from a thin-film process using crystalline silicon.

Variations on standard crystalline cells

Modifications to the standard format are easier than new concepts

The standard crystalline format can be modified to increase efficiency, improve temperature stability and/or capture a wider range of the spectrum. These modules will generate higher energy yields from a given surface area, which makes them attractive for the domestic and commercial grid-connect markets.

Modules include Sanyo's heterojunction with intrinsic thin layer (HIT), which is a monocrystalline wafer coated on both sides with a-Si to form the active cell; SunPower's back contact cells, which do not have a contact grid on the front of the cell (which shades active area); and BP's buried grid, which also reduces the shading effect of the top contact of the cell.

Modules are becoming bigger because it is more economical for manufacturers

Regardless of the specific technology, a module with two cells requires the same process stages as a module with 100 cells. For this reason modules have steadily grown in size over recent years as cells have become larger and production processes have advanced. The dollar per watt (US$/Wp) price typically quoted by a manufacturer is for their highest throughput module, rather than for their whole range.

Thin-film production

Thin-film is easier to produce in theory; either on glass or flexible substrates

Thin-film PV is produced by depositing the active layer directly on to a substrate, most commonly glass or metal foil, while R&D is focusing strongly on plastics. There is no requirement to grow an ingot, slice it into wafers and treat those wafers to form PV cells. In nearly all cases the cells are formed and interconnected as part of the production process, reducing complexity for production. Broadly, thin-film can be divided into modules with glass and those without. Both share generic advantages over the present dominant technology, crystalline silicon.

The reasons thin-film has such a bright future

Figure 6

Thin-film advantages over crystalline

Low raw material usage	A thin-film silicon cell is a few microns thick, compared to over 180 microns (0.18mm) for most crystalline cells. As the term suggests, all thin-film technologies make economical use of the core material, which is important for cost and availability.
High volume production	A complete module can be produced in a matter of hours with very little labour. Demand for PV within existing markets cannot presently be met, though emerging markets remain in their infancy due to limited overall PV availability.
Fully integrated production	The complete process from raw material preparation to final product can be performed in a single facility. In addition to volume, quality and consistency are (in theory) more controllable, which increases yield.
Low embodied energy	Energy payback for a commercial thin-film module is already less than one year in southern Europe.
Versatility	Modules can be produced to a given voltage and power requirement far more cost effectively than can crystalline. This massively increases potential applications and markets. It also allows product solutions to be more effectively produced.
Real life effectiveness	Thin-film technologies generate power more effectively than crystalline cells at low light conditions and at elevated temperatures. Thin-film formats also work better in shading. These properties widen geographical markets for a given product or solution and allow greater flexibility for the user.
High energy yield	More useable energy generated compared to crystalline modules of the same rating.
Ruggedness	Particularly for glass-free products, thin-film modules are poised to revolutionise a number of markets including the developing world and consumer electronics.
Smooth visual appearance	This varies between the technologies, though there is little inactive area on the module that prevents the matrix appearance of crystalline modules.

Source: Author

The major PV market sectors are described later, though first it is useful to understand the fundamental concepts behind PV technology deployment.

Driving the market

PV will succeed because it is better than what we have now

Simply put, PV will succeed because it is a better energy solution than those available now. And, thin-film technologies should establish PV across a broad range of sectors and applications, leveraging off its lower cost and more versatile formats.

Distributed generation

It's about fuel, not energy, and sunlight is everywhere so no need to transmit it hundreds of miles

One of the principal values of grid-connected PV is the ability to generate electricity at or very close to the point of use - ie, distributed generation. Our challenge today is one of fuel, not energy, and traditional central generation is very inefficient and wasteful.

Thin-film PV has significant potential for building mounted and building-integrated applications. PV windows, roof tiles, shades, cladding and other features will reduce the cost of incorporating the technology into new and existing structures.

Of the raw fuel that enters a power station, be it oil, coal or gas, we estimate that less than 15% of the embodied energy is actually useable by the end domestic or commercial customer. There are also huge environmental, financial and political costs of transporting the fuels to the central generating stations.

Distributed generation is one solution. A PV system can generate electricity a few metres from the point of consumption and, most importantly, the fuel is free.

Discussions of efficiency in regards to PV systems nearly always concern the module. A module or array may only be 15% efficient, but system efficiencies, that is the percentage of generated energy that can actually be used, are typically greater than 80%.

Benefits for utility suppliers

Utility electricity suppliers do not generally favour distributed generation as it reduces the amount of their core product purchased by the end user. However, one major benefit for the utilities is a reduction in spare capacity requirements.

Utilities can save billions in infrastructure costs by embracing PV

While the amount of national, centralised generation and transmission capacity for peak demand varies from country to country, 25% is an indicative value. This capacity is for high-usage periods such as breakfast and evening mealtimes, and during commercial breaks for major TV events.

PV in areas with high air-conditioning load is an easy opportunity

In countries with high cooling loads, PV can soften the demand driven by the use of air conditioners, which in some countries leads to repeated blackouts and brownouts during the summer months.

Distributed PV with storage can remove the need for peak capacity

Distributed generation coupled with on-site energy storage means properties can be configured to never use more than a certain value of energy from the grid and never use more than an agreed quantity during peak times. This is of enormous financial value in reducing the need to add or upgrade generating and transmission capacity. It also reduces grid energy distribution management costs.

Distributed energy storage, which can be the size of a washing machine, and intelligent home energy management systems are already available, allowing ever larger percentages of generation to be distributed without significant central infrastructure expense.

The role of the individual

People are greatest influence

As individuals, we will begin to examine energy efficiency as we have the content of foods, driven by carbon taxes, environmental concerns and the increasing cost of mains electricity. In tandem with a growing consciousness of energy efficiency and usage, the value of PV systems increases as a greater percentage of (ever lower) total consumption can be generated by a given system size. It is typical for domestic homeowners with a newly installed PV system to reduce their consumption by 10-30% simply due to heightened energy awareness.

Government policy stimulus

Many local authorities and some governments are actively introducing legislation requiring new buildings to generate a percentage of their predicted consumption on site. A building, for example, may be required to generate more than 10% of its energy from its roof and walls. Though this does not necessarily mean the use of PV, it is one of the most favoured technologies.

PV on new buildings could become mandatory

On-site energy generation can be compared to access for the disabled in buildings. Though 15 years ago this was considered too expensive and disruptive, it is a requirement in many countries today. Appropriate legislation is likely to drive similar acceptance of on-site generation.

Energy efficiency

Energy-efficiency measures immediately benefit PV

Energy-efficiency measures could reduce global electricity consumption by roughly a third. And, the more efficiently electricity is used, the greater the percentage contribution from a given PV solution or installed capacity, linking the value of PV systems to advancements in energy efficiency.

We generate in AC, consume in DC; forget the conversion inefficiency

Direct current (DC) home networks can improve home energy use efficiency by over 30%. Most home and office appliances actually run on DC, but have to include (usually inefficient) inverters to enable them to run on our mains alternating current (AC). PV generates DC, which also must be converted (using an inverter) to match the AC of the mains, though this is not required for DC networks. Directly powering appliances with DC would vastly improve the contribution of a given PV system to overall energy consumption.

Rural electrification

Rural electrification, or off-grid electrification, can apply to rural areas in industrialised countries but is most commonly used in reference to the developing world.

While the principle is the same as for distributed generation, in this scenario users are shifting from no electricity to owning their own energy solution that can provide quality lighting, cooling, learning (computers) and communication (radio/TV/internet) solutions. Energy for cooling, water pumping and purification, and powering tools can be crucial in driving local economic development. Improvements in healthcare are also a key outcome of rural electrification.

Thin-film technologies are well suited to meeting the primary requirements of the developing world, offering low cost, high volume, rugged construction and versatile electrical formats.

Carbon savings

Carbon trading is another important driver for PV systems, both on and off-grid. Carbon credits are valued at US$40-55 per tonne at present, with this set to rise significantly.

Emissions trading is becoming more important

CO_2 savings from grid-connected systems depends on the existing profile of electricity production for a given country. We assume a global average figure of 0.6kg CO_2/kWh.

Could be more valuable for off-grid applications

An off-grid system that replaces a typical diesel generator would save about 1kg of CO_2/kWh of output. For example, a telecoms repeater station (of which there are tens of thousands either installed or planned) typically uses a minimum of 10 kWh/day over a system life of 25 years (more than 9,000 days).

Also, kerosene, which is widely used in the developing world for lighting, cooking and heating, emits over 2.5kg of CO_2 per litre burnt. PV solutions replacing or preventing the purchase of kerosene are eligible for carbon credits.

Personalised energy

Tailored energy solutions are best achieved by the individual

Personal energy is energy generated on and/or for an individual or their piece of equipment. In developing countries the term also represents small home systems to power lighting, radios and refrigeration. The trend toward personalised energy is driven by economics, practicality, necessity and the moral and legislative aspects of sustainability and environmental concerns.

PV on bags, clothing or as a portable module can support the advancement of portable electronic devices. As power-hungry phones and PDAs incorporate more features, charging becomes more important and PV could allow users to recharge their devices on the go.

Compared to crystalline products, thin-film technologies are far easier to produce in smaller formats with tailored electrical characteristics. They capture more energy from low and indirect light, which means lower capacities are needed. Optimising the battery and load device (where possible) can lead to a much cheaper overall solution compared to the present offerings on the market. Optimised products hold particularly high potential for developing world regions where there are some two billion potential users.

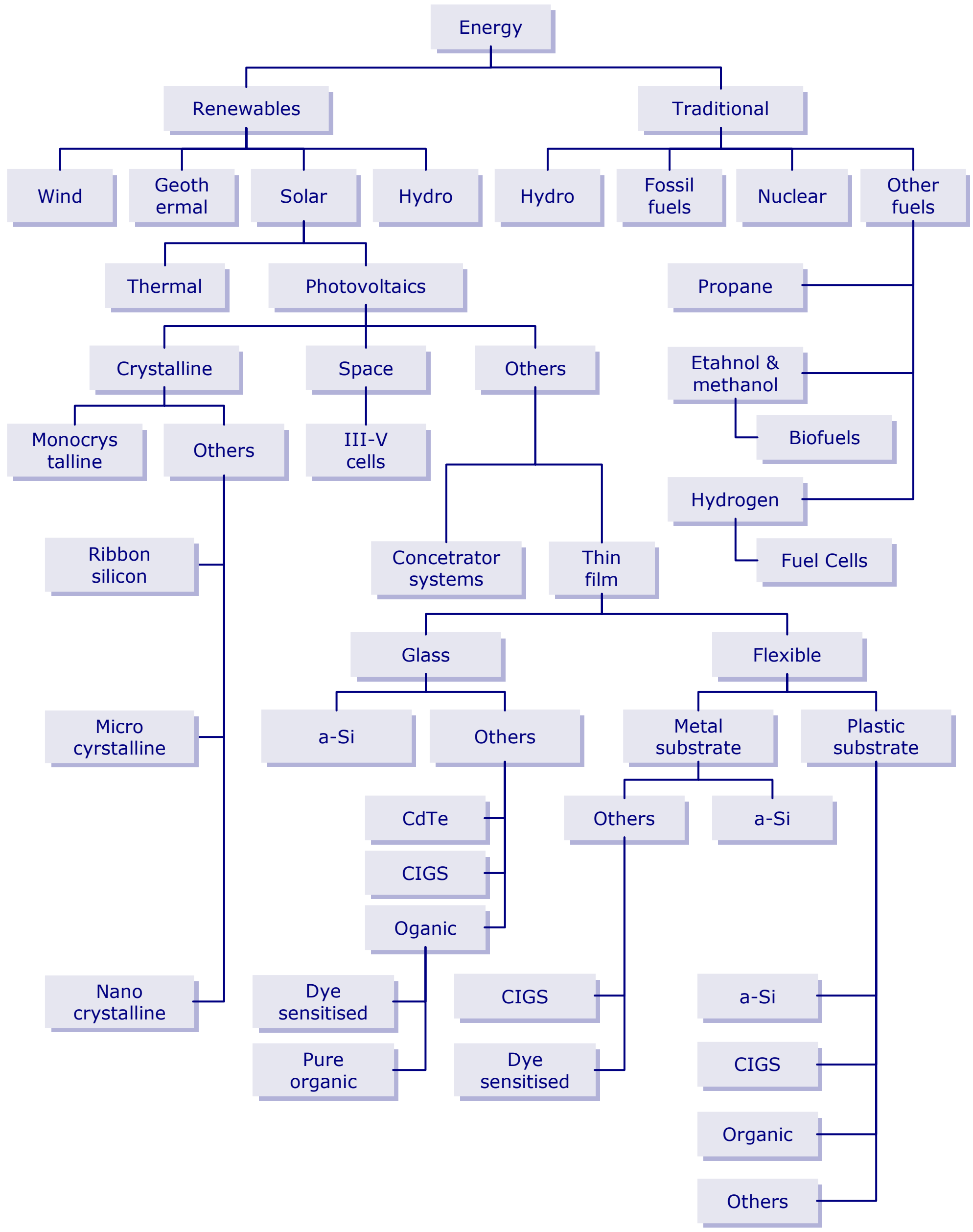
Bright future

Commercial thin-film modules have been in production since the 1990s, with small formats (ie, a few cells in series) in applications such as calculators dating to the mid-1980s.

From 'solar' to 'photovoltaics'

Figure 7

Top-down development of PV technology



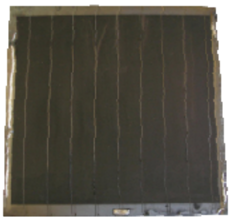
Source: Author

'Thin-film': Only three commercial technologies at present

Though many thin-film technologies are currently under development, only three major variants are commercially proven today. Since these have broadly similar structures and key production steps, R&D efforts can be applied across all three, though developers vigorously defend intellectual property.

Figure 8

The three major inorganic technologies



Amorphous silicon (a-Si)	
Pros	The science is well understood. Very energy-efficient production even compared to other thin-films. Raw materials are widely available and toxicity in production is low.
Cons	The primary disadvantage is low efficiency. Light induced degradation (known as the Staebler-Wronski effect) can be as high as 40% within the first six to 12 months[4].
Process	Scale up is largely focused on efficiency of process and manufacturing. The process uses chemical vapour deposition at temperatures <300°C. Benefits from advancements in the flat panel display sector (improvements in vapour deposition over large areas).
Additional	Dual and triple active layer cells can be produced to allow a greater section of the solar spectrum to be utilised. Initial degradation is far lower.
Manufacturers	Kaneka, RWE Schott Solar, UniSolar, Free Energy Europe and ICP.
Copper indium selenium (CIS)/copper indium gallium selenium (CIGS)	
Pros	Currently exhibits the highest efficiencies of all thin-film technologies; not susceptible to light-induced degradation (as with a-Si). Meets most environmental regulations for domestic refuge dumps as the amounts of selenium and cadmium used are negligible. Good black uniform appearance.
Cons	A number of process issues must be addressed for costs to decline. Potential shortage of indium as volumes increase[5]. Sensitive to moisture. Good sealing is important; especially for flexible PV. Suffers stability problems in hot and humid environments. Includes a cadmium buffer layer.
Process	The active material can be deposited using around 10 different deposition methods at temperatures <500°C.
Additional	Manufacturing scale-up issues have frequently prevented companies from successfully using high efficiency cell recipes for commercial production. Better understanding is required for the effects of deposition processes, choice of cell structures, module performance and device stability.
Manufacturers	CIS Solartechnik, EPV, Global Solar, HelioVolt and Würth Solar.
Cadmium telluride (CdTe)	
Pros	Lowest production costs among the current thin-film modules. The most attractive features are its chemical simplicity and stability. Production is relatively straight forward, especially compared to CIGS. Little degradation if production is well controlled.
Cons	Dangers of cadmium (real and perceived). Small modules at present (<80Wp).
Process	Temperatures 500-600°C using a variety of deposition methods.
Additional	Manufacturers legally committed to take back modules at the end of their life (whenever that may occur) for recycling in an environmentally conscious way.
Manufacturers	First Solar, AVA Solar, Antec Solar Energy, Calyxo, Primestar.

Source: Author

Question of efficiency

Stated efficiency figures are a guide only

Efficiencies for technologies, whether cells, modules or products, are difficult to state with any accuracy. Cell and module ratings have a tolerance (±5% typically) and suppliers have a range of product capacities depending on the effectiveness of the process. The higher the size-to-power ratio the more efficient the actual technology is.

Future efficiencies dependent on the process, not the science

The figures in the table below are based on a number of reported efficiencies from manufacturers' web sites, national and international agencies and industry media. There are variations even in stated existing products, so predictions of future efficiencies assume a number of factors. Reaching the stated efficiencies achievable within the next five years requires an emphasis on production process and machinery, not on the pure science of the technology.

[4] Module power rating should take account of initial degradation. Many manufacturers heat-soak products to accelerate initial degradation and bring the module to a stabilised state.

[5] Indium is relatively rare and expensive. About 70% of current production is used by the flat-screen industry. There is concern production of CIGS will be limited by Indium availability.

Figure 9

Reported efficiencies for PV technologies

(%)	Cell efficiency	Module efficiency	Laboratory cell efficiency	Future commercial Production modules
a-Si single junction[1]		5-6	10	8
a-Si dual junction[1]		5-7	12	9
a-Si tripe junction[1]		6-8	13	10
a-Si/mc-Si		7-9	12	10
CdTe		8-11	17	13
CIGS		9-11	20	16
Dye sensitised	7	3-5[3]	12	7
Ribbon silicon	11-14	10-13	20	15
Poly-crystalline	14-15	12-14	21	17
Mono-crystalline	15-17	13-15	25	17
Non-standard silicon[4]	16-21	15-18	23	19-20
III-V cells[2]	~27	na	40	33

[1] In stabilised state. [2] Measured with concentrated irradiance. [3] Small production runs. [4] Modified crystalline formats such as SunPower back contact, Sanyo HIT, BP buried grid. Note: Standard test conditions: 1000W/m^2, 25°C, air mass 1.5. Solar cells and modules are rated by their performance at STC. Source: Author

Claimed cell efficiencies are becoming more exaggerated and damaging the industry

Claims of cell efficiencies, particularly those citing world records, are often exaggerated. This is a concern since it raises expectations and lures investment away from companies with lower reported numbers. Not only are these efficiency claims well above those of a typical cell being produced, they increase the gap between laboratory claims and achievable performance from commercially produced products.

Even when not exaggerated, they can be misleading

Assuming cell efficiencies can be verified and have not just been exaggerated for commercial purposes, there are several technical reasons for these over-hyped claims. First, cells are rated using artificial light, not the sun. They are more sensitive to certain wavelengths of light and will therefore perform better if tested with full intensity at these wavelengths (which does not occur in real-life conditions.) Also, heating effects are often prevented by flashing the test light and/or cooling the PV sample. Finally, test cells are small and produce very low values of voltage and current. The lower the values, the more tolerance the reading will have in many cases. These factors alone can contribute to reported values 10-40% too high.

Costs in theory

Future costs are deliberately not stated - they are theoretical and no better than crystalline

Media and industry analysis of these new technologies tends to concentrate on future costs. Commonly quoted cost figures have become strap lines for manufacturers. All technologies, including the dominant crystalline format, which presently costs more than US$3/Wp, have the potential to cost less than US$1/Wp within a decade; or less than US$0.5/Wp within two decades. Yet this is academic to a large extent since hundreds of assumptions are made in order to predict future costs for emerging PV technology and it is these assumptions that define a company's potential.

Cost targets are memorable but often misleading

Cost targets tend to be either memorable values such as US$1.5/Wp, less than US$1/Wp and less than US$0.75/Wp, or comparative values such as 'grid parity' or the present crystalline cost. The latter two are not fixed or universal. Grid-parity cost depends on the climate and commercial situation of a region, while crystalline costs vary even within a manufacturer's product range.

A chart of future or even present costs would have too many disclaimers to be credible

It is tempting to include a chart showing potential costs per watt but it would contradict this report. We raise commercialisation challenges at a later point, though it is reasonable to summarise the issue. Four primary factors define the US$/Wp cost of a product: production consistency/yield; product efficiency; material costs; and product stability. Any one of these can (and does) prevent economic production completely or have a more than 100% effect on the final product cost.

Nanosolar: Best-know firm that did not deliver as promised

Nanosolar received considerable media attention after promising to produce CIGS on a flexible substrate, but has so far failed to produce commercial product. Five years ago, it thought US$100m would deliver more than 50MW of production at roughly US$1/Wp, yet more than US$600m later it has revised its cost and throughput figures numerous times. The situation mirrors that at Miasolé, Konarka, Spheral Solar, G24 Innovations and many others that have failed to reach market.

Until in commercial production, technology costs per watt are targets, not predictions

Over the past ten years few predictions (and perhaps none) of price and capacity have been accurate until volumes were already past pilot production (at more than 500kWp). As such, US$/Wp figures can only ever be considered targets rather than predictions.

Amorphous Silicon (a-Si)

The original thin-film and still the only one widely produced

Not only is a-Si the most dominant of the thin-film silicon (TFSi) formats, it is the most proven. Glass modules are by far the most common, though they are set to lose market share to the more efficient CIS and thin-silicon formats. Flexible a-Si is a growing sector with significant potential.

Figure 10

Summary of technology

	Commercial module	Comment
Efficiencies	5-8%	Stabilised
Size	Up to $0.8m^2 \times 2.44m^2$	Modules typically $<2m^2$ due to handling difficulties
Thickness	1-4mm	Metal substrate are thinner
Appearance	Uniform	UniSolar modules can be blue with violet toward edges
Colour	Reddish brown to blue or blue-violet	Ditto

Source: Author

Flexible modules

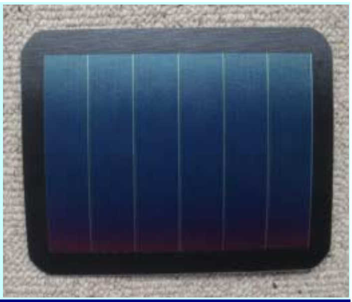
Truly flexible PV is in huge demand, but modest production at present

Despite the promise echoed in press reports, module volumes are very low, keeping costs high. Steel foils are used at present, though plastics would be ideal for portable and consumer goods. With a better understanding of roll-to-roll production, large volume increases are likely.

UniSolar

A subsidiary of Energy Conversion Devices (ECD), United Solar Ovonics (UniSolar) was the first company to produce flexible thin-film at volume. In the late 1990s, volume was limited, but now exceeds 120MWp. Its triple junction technology uses a stainless steel substrate.

UniSolar started with a range of small modules from 1Wp to 128Wp, but it has steadily migrated to larger capacities, including aluminium-framed products. It stopped producing small modules in 2006 to focus on grid-connected applications.



Source: Author

Flexible formats less efficient, more expensive, and have shorter lives

Figure 11

Flexible conversion efficiencies

(%)	Single junction	Dual junction	Triple junction
Flexible substrate			
Commercial modules	3-5	~5	6-8
Laboratory cell efficiency	9	10	13
Future commercial production modules	5-6	7	9
Rigid/glass substrate			
Commercial modules	5-6	5-7	6-8
Laboratory cell efficiency	10	12	13
Future commercial production modules	8	9	10

Source: Author

Major manufacturers

- Single junction: Dunasolar, Kaneka, RWE Schott Solar, Sanyo, Solar Cells
- Dual or tandem junction: EPV, EPOD
- Triple junction: ECD Ovonics (UniSolar)
- Flexible: UniSolar, Iowa Thin-film Technologies (Power Film), VHF Technologies (Flexcell)

Other leading manufacturers include BP Solar, Canon, Free Energy Europe, Fuji Electric, ICP, MHI, Shenzhen Topray Solar, Sinonar, Terra Solar, Tianjin Jinneng Solar Cell.

Other thin-film silicon (TFSi) technologies

There are several TFSi technologies in development, driven by the silicon shortage

Aside from the dominant a-Si, TFSi modules are also based on silicon-germanium (a-SiGe) alloys, microcrystalline silicon (μc-Si or mc-Si) and large-scale recrystallisation of silicon. Combinations of these and the use of multiple layers improve conversion efficiencies.

Crystalline silicon thin-film

Aiming to benefit from the manufacturing advantages of thin-film and the material advantages of crystalline silicon, high-quality silicon films are produced on a cheap substrate (glass, metal or plastic), using up to 90% less silicon than traditional cells. These technologies are largely being developed by existing crystalline and thin-film producers since they employ similar basic processes. While several production methods are under development, the technology is not yet cost competitive with high-volume crystalline products, but is catching up, especially due to the low silicon requirement.

Some are in production, but they are more like crystalline cells

The high temperature approach (900-1,000°C) is already used in the production of Apex cells[6], which are similar to polycrystalline with efficiencies of up to 16%. Based on wafers, they are strictly classified as crystalline cells. Microcrystalline production employs a low temperature approach (200-600°C), which allows cheap (and possibly flexible) substrates, and achieves around 8.5% efficiency.

Others becoming commercially successful in absence of volume thin-film

The current favourite is micromorphous, the combination of microcrystalline and amorphous (a-Si/mc-Si), demonstrating cell efficiencies of 12%. Kaneka offers commercial modules with 9% efficiency, while Sharp is increasing its micromorphous capacity from 15MW to 160MW this year. It is not yet clear

[6] Apex cells were pioneered by AstroPower (Delaware, USA), which declared bankruptcy in February 2004 and was subsequently acquired by GE.

what market position this technology will take, though it may fill a gap until true thin-film competition emerges at scale. Other suppliers include Mitsubishi Heavy Industries, Sinonar Solar Corp, Sontar, Suntech and Xunlight.

Turnkey systems are crucial to reducing product cost

Applied Materials

Micromorph (as well as a-Si) turnkey production systems are being promoted by companies such as Applied Materials, Oerlikon and Ulvac, though these entail a significant commissioning effort by recipients.

Turnkey systems are crucial to reducing product cost. Installation and commissioning can take as little as four months, and is crucial to determine capital returns. Larger deposition (>1.5m²) is desirable, but more difficult to commission for volume.

Source: Author, Applied Materials

CSG Solar AG, Germany, began producing crystalline silicon on glass (CSG) thin-film solar cells in 2006. Active layers are deposited then heated (600°C) to form a polycrystalline layer. A number of process steps require refinement though initial modules have efficiency rates of just under 9%. Estimates put efficiency at 12-13% in the next few years, or up to 18% for triple junction cells.

Copper indium selenium (CIS and CIGSS)

Most promising; but most difficult to produce

CIS is often alloyed with gallium and/or sulphur to form CIGSS/CIGS. The use of gallium increases the effectiveness of the cell, but complicates the manufacturing process.

Efficiency potential is high, though production challenges remain

Figure 12

Summary of technology

	Commercial module	Comment
Efficiencies	9-11%	Stabilised
Size	0.6m² x 1.2m²	Limited production at present. Larger is possible
Thickness	2-4mm	On glass. Flexible formats <2mm depending on substrate
Appearance	Uniform	
Colour	Dark grey to black	

Source: Author

Only partially flexible formats available

Flexible formats are relatively limited (the majority are glass), though Global Solar produces >70MW using a steel sheet substrate to offer a degree of flexibility. Nanosolar promotes a flexible product using a proprietary metal foil substrate. Solarion and Daystar already offer flexible products.

Global Solar is only producer of commercial flexible products

Figure 13

Flexible products

Global Solar	Nanosolar	Daystar solar

Source: Companies

Figure 14

Existing and potential conversion efficiencies

Flexible substrate (%)	
Commercial modules	3-4
Laboratory cell efficiency	9
Future commercial production modules	6
Rigid/glass substrate (%)	
Commercial modules	9-11
Laboratory cell efficiency	20
Future commercial production modules	16

Source: Author

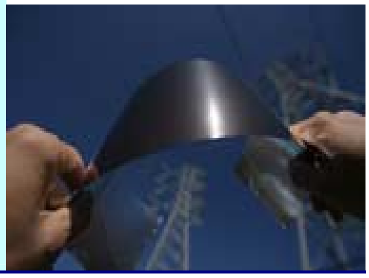
Lots of R&D with lots of finance, though still no volume production

Over 35 companies worldwide are actively developing CIGS PV technologies, including Ascent, CIS Solartechnik GmbH, Daystar, EPV, Global Solar, HelioVolt, Honda Soltec, Miasolé, Nanosolar, Showa Shell, Solarion, SoloPower, Solyndra, Sulfurcell, Würth Solar.

Despite more than US$600m in financing Nanosolar has yet to produce commercial volumes and may not be able to

Nanosolar

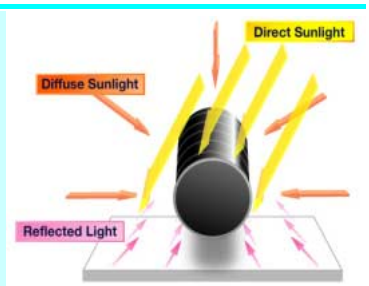
The company this year attracted US$300m in financing after spending several hundred million over the past five years. The technology it is attempting to produce - CIGS - has the most potential in a flexible format, but is extremely difficult to produce on glass and using a flexible substrate exacerbates the challenges. Little (maybe no) commercial product has been sold, and it is likely to be several years before Nanosolar can reach the more than 100MW low-cost production it is promising; assuming it can do it at all.



Source: Author, Nanosolar

Solyndra

Solyndra has begun selling a tube-shaped CIGS product comprised of two cylinders. The inner cylinder is coated on the inside with the active CIGS layer and the outer transparent tube directs the light to the active surface. This allows 360-degree generation on each tube, which can capture direct, diffuse and reflected light. The company claims efficiency rates of 12-14%. Very little information on performance is available, and the concept seems flawed since it is less efficient with direct light than standard modules.



Source: Author, Solyndra

Cadmium telluride (CdTe)

Figure 15

Summary of technology

	Commercial module	Comment
Efficiencies	8-11%	Stabilised
Size	0.6m² x 1.2m²	Limited production at present. Larger is possible
Thickness	3-4mm	Non-hardened glass
Appearance	Uniform	
Colour	Reflective dark green to black	

Source: Author

Manufacturers insist the technology is safe, though public not convinced

There is intense discussion regarding the market acceptance of the use of cadmium. Since processing this by-product of copper, lead and zinc mining into CdTe creates a harmless compound, this could arguably be viewed as ecologically beneficial. CdTe is described as non-toxic and very stable, even at high temperatures. If a CdTe module was in a fire, in theory, not only would the cadmium be safe up to its breakdown temperature of around 1,000°C, it would be encased in glass, which melts at a much lower temperature.

Perceptions, however, are difficult to gauge. CdTe modules are unlikely to be widely accepted for domestic and small-commercial installations, so manufacturers are targeting large-scale installations with the emphasis on lower costs than competing products.

Major manufacturers of these products include First Solar, AVA Solar, Antec Solar Energy, Calyxo, Primestar.

Products are small but cheap; cost will need to remain low

First Solar

The first company to produce commercial CdTe modules at low cost of less than US$1.30/Wp, First Solar took advantage of a global module shortage and high demand to overcome a reluctance to use a small cadmium product. Module sizes are less than 80Wp (200Wp is more typical), which makes large systems far more complicated. The company has secured a handful of large orders to justify production expansion. As competitive products become more available and less expensive, First Solar will need to keep costs proportionally low.

Source: Author, First Solar

Emerging technologies

No guarantee technology will reach commercial volume

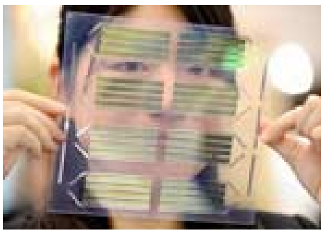
Emerging technologies are those where at least one 'proof-of-concept' exists and can be considered longer-term options that will disrupt the development of the two established cell technologies: crystalline silicon and thin-film solar cells.

Novel technologies are ideas and developments that could potentially lead to the creation of disruptive technologies. It is very difficult to assess these concepts in terms of future cost, efficiency and end-product performance.

Organic photovoltaics (OPV)

The ultimate; we are decades away from the true potential

OPV has the greatest potential of all PV technologies, based on nano-sized active domains that allow a radical increase in the capture of light energy. They use very small volumes of active materials, though the many nano-material options are in development. In May 2008, NanoMarkets predicted the OPV market would generate US$1bn in revenue by 2015, which would require significant investment.



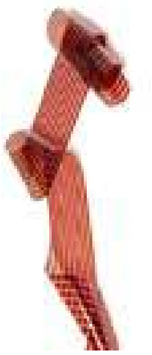
Dye sensitised solar cells (DSSC) are often included within the organic PV family. However, since they contain inorganic materials (ie, non-carbon-based substances), some describe them as 'hybrid' organic cells. OPV, and to a lesser extent DSSC, have the potential for very low cost active layer material (dyes and titanium dioxide), low cost substrates (plastics), low energy input and easy up-scaling. Electrically conductive polymers (hydrocarbon polymers) are central to the technology.

Figure 16

OPV technologies

Pros	Flexible, lightweight and as thin as plastic films. Can be variable in colour, allowing a logo or pattern to be incorporated, though this has a significant efficiency cost. High volume roll-to-roll printing processes could increase throughput by a factor of 10-100 compared to other thin-film approaches. Will eventually be produced and incorporated into products such as bags, umbrellas, tents and even clothing.
Cons	Difficult to produce commercially. Materials are not yet available in volume - particularly conductive polymers.
Performance	Present laboratory efficiencies are 2-5%; 10-15% is possible, though will take many years to achieve.
Production challenges	The challenge is the use of materials which will interact with each other. The dye, electrolyte (which is often corrosive), substrate and encapsulation must all be stable when packaged together. Selection of materials is therefore crucial and is the limiting factor to efficiency, long-term stability and manufacturing cost. These are the preconditions for the commercialisation of organic solar cells.

Source: Author



The Nobel Prize for Chemistry was awarded in 2000 for the discovery and development of conductive polymers.[7] This created a great level of interest and subsequent R&D in OPV.

It should be noted that the polymers are derived from oil and discolour in sunlight over time. Alternatives are being sought from natural and renewable sources such as soybean oil, linseed oil, sunflower oil, etc.

There is a huge amount of research being conducted in this area. For example, the German Federal Government and companies such as BASF, Bosch, Merck and Schott are following a joint high-tech strategy and planning to invest around €360m into OPV with the intention of manufacturing solar films industrially by 2015.

Shift from DSSC to OPV; aiming for 1GWp by 2010; this is highly unlikely

Konarka Technologies

Konarka initially developed dye sensitised technology, but sold the manufacturing rights to G24 Innovations (see below) in June 2006 and is now focusing to OPV.

Konarka announced the opening of a 1GWp facility in September 2008, set to be in production by 2010. Despite a talent for obtaining finance the commercialisation process is incredibly challenging. It is highly unlikely it will produce anywhere near capacity in the first few years.

Source: Author, Konarka

Major manufacturers include Heliatek, Dyesol, Konarka and Plextronics. Fundamental R&D is still required and therefore involves numerous academic institutions. For example Konica Minolta, Micro-tec, NEC, Nissan Chemical Industries, SEL, Sharp and other companies are backed by leading Japanese universities.

[7] Alan J. Heeger, Alan G. MacDiarmid and Hideki Shirakawa

Dye sensitised solar cells (DSSC)

Notable organisations involved in the production of DSSC include Konarka (small demonstration samples), STI/Dyesol (materials), G24 Innovations (attempting commercial production), Greatcell Solar, Peccell (cells and research). First demonstrated in the early 1990s, DSSC is fundamentally different to conventional solar technologies. Instead of using silicon as the active material, these systems absorb light in an organic dye similar to the way plants use chlorophyll to capture energy from sunlight. This dye is used with an electrolyte and titanium dioxide (TiO2), which is commonly available.

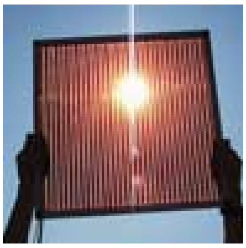


Figure 17

Dye Sensitised Solar

Pros	Very sensitive to low light and therefore very tolerant of poor incident angles and shading. Stable at elevated temperatures, unlike most other technologies. Production is not so dependent on clean room conditions. Potential for printing active layers, though not yet possible.
Cons	Low efficiency. Stability is low due to sensitivity to moisture and oxygen. Dyes must be produced in large volumes for the first time to allow scale-up. Electrolytes are corrosive and present significant challenges at volume.
Performance	10.4% laboratory cells, 4-5% pilot production.
Flexible formats	Demonstrated on a small scale (Konarka), though commercial production has so far proven too challenging.

Source: Author

G24 Innovations

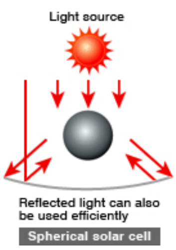
G24 are the first company to attempt DSSC production commercially. As with Nanosolar they are trying to move straight to a flexible format. DSSC is not proven on glass commercially and has stability issues that become critical for flexible encapsulation materials.

Many believe DSSC cannot be produced at high volumes on a flexible substrate with useable performance.

Source: Author, G24 Innovations

Spherical solar cells

Two companies are prominent in the production of this technology: Kyosemi Corporation, of Japan, and Spheral Solar Power (SSP), a division of ATS (Automation Tooling Systems) of Cambridge, Ontario. Neither has produced commercial volume, though SSP released modules in 1994 for a limited time.



The production of these cells employs minute silicon beads (of less than 1.2mm in diameter) bonded in a matrix to aluminium foil sheets or between transparent conductive polymers.

Figure 18

Spherical solar

Pros	Reduced silicon requirement. Increased relative performance at low sun angles and in diffuse light.
Cons	Difficult production process results in low yield and low efficiency.
Performance	Kyosemi has demonstrated cells with roughly 12.5% efficiencies, while SSP have reached around 9.5%. SSP modules were about 4% efficient when briefly released in 2004. Both are promoting flexible formats of the technology, though neither have committed to commercial production.

Source: Author

Sliver cells
Origin Solar in Australia is developing sliver technology and released 10Wp modules for a short time in 2007, before withdrawing them. Sliver cells are based on a 1mm thick monocrystalline wafer, from which strips of 0.05mm are etched to create active PV elements. These strips or slivers, in the order of 10cm long, 1mm deep and 0.05mm thick, are detached from the wafer and arranged between two sheets of glass.

Figure 19

Sliver solar

Pros	Around one-seventh the silicon of conventional wafer cells. Active on both sides. Versatile electrical formats. Modules can be made semi-transparent.
Cons	The process is expensive and the lack of economies of scale will prevent commercial success.
Performance	Laboratory efficiencies up to 19%. Production modules are expected to reach efficiencies in the region of 10%.

Source: Author

Novel technologies

These are still theoretical, though some may arrive quickly

Advances in nanotechnology and nanomaterials have produced exciting opportunities for PV cell design. The innovations are not necessarily new concepts, but are often high-efficiency versions of existing formats.

Active layer concepts
Nanotechnology allows very small dimensionality to be introduced into the active layer, better matching the incoming solar spectrum or modifying the spectrum for the device. Terms such as quantum wells, quantum wires and quantum dots are becoming more common in PV literature.

Theoretically, efficiencies exceed 50%, though basic material development is still the focus of R&D. These concepts will benefit from parallel development in established and emerging PV technologies, and from the microelectronics sector. Some of these technologies will suit concentrator systems since they will probably perform well under high intensity illumination.

Boosting existing PV technologies

A 'bolt-on' improvement to existing technologies may speed commercial development

PV cells perform at higher efficiencies for certain wavelengths of light. Tailoring the light entering the PV module to the most effective wavelength for the given cell type could significantly increase efficiency.

Once again nanotechnology will play a part. Research is in the early stages, but in theory the technology can be 'bolted on' to existing devices (crystalline and thin-film cells), significantly shortening their speed to market. Efficiency increases of more than 10% above the existing PV cell technologies are predicted, while production and implementation could be low cost.

Areas for further R&D

Focus for development in the near term

Improvements in materials, processing and packaging are being researched and developed across the whole industry; from academic institutions to major manufacturers. However, developments for implementation within the next few years are targeting the following:

- Higher module efficiency
- Lower module cost
- Consistent production

- Higher throughput of production
- Improved module stability and life
- Lower energy use
- Improved environmental footprint

Thin-film immediate issues for development focus

We see considerable potential for cost reduction in thin-film PV. It may take more than a decade but thin-film will ultimately surpass crystalline in terms of cost and volume. Sustained commercial growth will require an understanding of several fundamental areas, with particular R&D focus required on the following:

- Understanding of fundamental materials and interactions
- Reliable, cost-effective production equipment
- In-process monitoring and control (consistency and cost)
- Reliability of products (through advanced testing)
- Low cost packaging solutions (rigid and flexible)
- Recycling of materials and old modules (cost and volume)
- Replacements for scarce substances such as Indium

See Appendix 2 for primary research areas for each major technology. We also include a list of crystalline research areas.

From lab to market

Delays, overspending and even failure

For PV technology, making the transition from laboratory to commercial reality is expensive, time consuming and requires a great deal of innovation and adaptation. Principally, it requires a great deal of patience. There are literally thousands of interconnected scientific, engineering and commercial issues that can hinder success and the process must be conducted as a methodical coordinated project with continuous status assessments.

All too often it is self-imposed pressure from shareholders, marketing and commercial departments that drive a company to take shortcuts or raise unrealistic public expectations. Nanosolar, Miasolé, G24 Innovations, Spheral Solar and Konarka have all coupled a strong media presence and financing - well over US$1bn collectively and two decades in the limelight - with no production to speak of. The most promising technologies and formats raise expectations the most, but also tend to be the most difficult to actualise and the least-proven concepts.

Glass versus flexible formats

Using glass before flexible substrates is almost a necessity

As a substrate, glass is far easier to work with than a flexible material such as metal foils or plastics. Not only is glass very flat, rigid and clean, it can be used with thermal processes and corrosive materials, and significant opportunities for high-volume and low-cost manufacturing already exist in this space.

Companies attempting to achieve commercial production for the first time using flexible substrates face significant challenges and usually need further investment and a reassessment of timescales and end-product expectations. Indeed, some technologies cannot be transferred from laboratory glass cells to commercial flexible modules without cell redesign. For example, organisations attempting to by-pass the use of glass include Spheral Solar (crystalline); Nanosolar and Miasolé (CIGS), Iowa thin-film (a-Si); Konarka and G24 Innovations (dye sensitised).

Roll-to-roll production

Roll-to-roll production exacerbates the challenges of reaching commercial production

The production of gigawatts of high-efficiency thin and flexible PV costing just a few cents per watt is decades off. However, roll-to-roll production holds the promise to make this a reality. At present over 99% of commercial PV is glass-based, despite billions of dollars of investment in flexible-format producers.

The raw material is typically around 30cm (12”) wide and hundreds of metres long. The substrate is fed into the front of the machinery and the active materials are deposited and treated as the substrate is pulled through the various process stages. Packaging/environmental protection is the final stage. The finished material is either coiled up and removed from the machine for finishing elsewhere or cut into modules. After the cutting stage it is usually necessary to seal the ends of the modules.

Figure 20

Roll-to-roll production

Pros	Modules are flexible; with no glass or frame, but also lightweight and very thin. Very high volumes are possible, though UniSolar is the only company yet to demonstrate this.
Cons	Very difficult to commission machinery to required tolerances within the limits of the materials and active elements. Wider material production drastically reduces consistency. The process requires a great deal from the materials; physical and thermal stresses, particularly the substrate and packaging (encapsulation).

Source: Author

Testing of finished, uncut production is a major barrier to economical success

A big problem with roll-to-roll production is that it is not yet possible to fully assess sections of finished material prior to cutting it into modules. The module length defines its power (ie, Wp). If production is consistent, each module cut to the same length will have the same power rating. If consistency varies, however, a given cut length will result in modules with different ratings, meaning that lower-efficiency sections may not meet the minimum power requirement of a product, while higher-efficiency sections will be overpowered, resulting in waste. Either way this narrows a producer's margins.

Pilot production

Pilot production using machines designed for scale-up is almost a necessity

Laboratory concepts need to be trialled at a pilot production level before a company can proceed to even small-scale commercial production. Production of more than 100kW using machinery designed for scale-up is key to making the move from the lab more manageable. This is especially true for roll-to-roll machinery; it cannot simply be a large machine running very slowly.

Start small and ramp up

UniSolar, Iowa Thin-film, Flexcell and Global Solar all supply 'flexible' products, starting out with limited commercial volumes (less than 500kW). This was not necessarily by plan, though funding prior to 2005 was far more difficult to obtain. Forced to recognise the theory was far easier than the practice, less media attention for PV at the time also meant that they did not have the same promises to live up to.

Source: Author, Flexcell and Konarka

Life expectancy considerations

Under ideal conditions, a PV cell may have an operational life of decades. When that same chemistry is produced in a factory environment with all the inaccuracies of a volume process, the life of the same chemistry can be significantly reduced. This reality applies to all thin-film materials. Dye solar cells, for example, have operated in the laboratory for over a decade, but all attempts to produce the same chemistry commercially have so far been unsuccessful.

Quoted life for the base technology offers little insight into the life of a newly produced format

Manufacturers of new technologies refer to accelerated life tests conducted by respected research institutes. These tests are often for the base technology concept, rather than the commercially manufactured product, and may be on a single cell, handmade and sealed on both sides with glass.

Simulating real-life stability is indicative only

Testing a PV module type to ensure it will perform for over two decades is very difficult since, while accelerated testing is very informative, it is not a guarantee. It cannot account for the 'human' element, for example. The warranty of a new technology is therefore very important as it is a legal document for the manufacturer and the customer.

Inherent challenges

The primary reasons why thin-film is still in limited production, despite significant investment

Figure 21 offers an insight into the complexity of bringing a technology to market. In most cases, roll-to-roll processing makes things more difficult. It is not possible to predict the likelihood of success for any emerging technology without specific technical due diligence. However, any one of the issues outlined in Figure 21 can result in significant delays, large cost increases or even prevent the concept from becoming commercial reality.

Figure 21

Challenges for realising commercial thin-film production

Multiple cells can adversely effect each other	Active materials are developed at the cell scale - the size of a thumbnail. A cell is typically around 0.5V but commercial modules require multiple cells to be fabricated in series to increase voltage. (The ability to do this is a prime advantage over crystalline module production). Detrimental cell interaction is sometimes only discovered during pilot production.
Cleanliness and control in the lab is difficult to transfer to commercial production	Thin-film technologies rely on the purity and consistency of the primary ingredients for efficiency and stability. A laboratory or even a small pilot production line has natural benefits of cleanliness and quality control. The primary ingredients are used in small quantities and therefore supplied, transported and stored in clean vessels. The small quantities allow a high percentage to be tested for purity. There is little risk of issues such as contamination or stratification. At commercial scale it is nearly impossible to replicate conditions of cleanliness simply due to the volume of the products needed.
Unprecedented material volumes cause consistency problems	In the case of materials such as dyes (for dye sensitised and organic PV) little experience exists for dealing with large volumes. Supplier material tolerances need to be established and the upper and lower values assessed for their effect on the final module performance.
Production equipment is difficult to commission	Production equipment plays a crucial role in cost reduction. The equipment directly affects product volume, yield, consistency, throughput and embodied energy. Indirectly it can define properties such as life, stability and versatility. Thin-film production stages may be familiar but the level of precision and consistency are challenging. Even bespoke machinery needs to be refined during commissioning.
Materials at high volumes can require supplier capital investment	Research volumes of material are generally obtainable from established suppliers, or can be produced to order by a selection of (albeit specialist) suppliers. For production volumes investment is required by the material supplier. Substrates such as conductive polymers, titanium foils and even stainless steel, especially when thickness and purity requirements are challenging, can prove expensive and difficult to obtain.
Volume means production speed, which reduces consistency	Production of cells and modules at the R&D level is not generally time constrained. There is also a high level of user control for each stage of production. When attempting to significantly increase volumes, production tolerances and consistency limits need to be established. There can be unforeseen effects to efficiency and life that can only be understood through the use of in-process monitoring and control.
Legislation can limit pilot production and require significant testing and approvals	Legislation such as Restriction of Substances Hazardous to Health (ROSHH) will allow small quantities of a given substance to be imported and used. If materials such as cadmium or ruthenium are to be imported in volumes and incorporated into commercial product, licences need to be obtained. A licence will require proof that the hazard is within acceptable limits throughout the supply and manufacturing processes and within the final commercial product. This is one of the reasons First Solar has a commitment to safely dispose of all of its modules (which contain cadmium) at the end of their operational life. It is producing millions of units with lifetimes in decades for deployment in all parts of the globe to numerous commercial customers . . .

Source: Author

PV in real life

Thin-film works better in real life than crystalline. All PV technologies are affected by the environment and particularly temperature, though the extent of the effect is not conveyed by the rating of the product. Pressure and vibration from storage and transport are also important.

Module rating

All commercial PV technology is rated at standard test conditions (STC). The primary parameters are: 1,000W/m² irradiance; 25°C ambient air; air mass 1.5 (AM), to simulate the atmosphere and spectral distribution. The real-life performance advantages of thin-film are not highlighted by STC, with these tests actually favouring crystalline.

Figure 22

Limitations of rated performance

Module peak power (Wp)	Generation at STC - PV cells do not heat up. Actual power should be within a stated percentage of the rated power. This is as low as ±2% for well-proven technologies and as high as ±10% for others.
Degradation	At the end of the performance warranty period, actual output should be within a stated percentage of the rated power. This is typically 80% after 25 years, though specifics vary for technologies and suppliers. Initial power can be higher than module rating to compensate for degradation.

Source: Author

The rating of a PV module biased toward crystalline

Thin-film generates more electricity per peak watt capacity. Using Wp, rather than watt-hours (Wh) generated, to rate modules is analogous to using miles per hour instead of miles per gallon to rate a car. Also, the rating makes no mention of low light response. Crystalline requires a minimum threshold of light before effective generation commences, whereas the thresholds for thin-film are far lower. Of the many parameters tested, rated power and the rate of degradation are the most important.

Temperature effects

During the test the light is flashed for a split second so the module does not heat up. For a module operating in air temperature of 25°C, the actual PV surface will be 20-24°C hotter.

Temperature reduces efficiency; effect different for each technology

This is true of most commercial PV, known as the normal operating cell temperature (NOCT). Power declines by a percentage of the total rating for each degree centigrade above 25°C. Values vary for specific manufacturers and technology variants, but we outline representative data in Figure 23.

Figure 23

Power reduction when operating at increasing ambient temperatures

	Temperature coefficient (%/°C)	Power loss at each ambient temperature		
		25°C (%)	35°C (%)	45°C (deserts) (%)
a-Si (1, 2 & 3 jnc)	(0.20)	(4.40)	(6.40)	(8.40)
CIGS	(0.46)	(10.12)	(14.72)	(19.32)
CdTe	(0.27)	(5.94)	(8.64)	(11.34)
Crystalline	(0.45)	(9.90)	(14.40)	(18.90)
Sanyo HIT	(0.33)	(7.26)	(10.56)	(13.86)
SunPower	(0.34)	(7.48)	(10.88)	(14.28)

Source: Author

Certification

Certification standards need to be updated to become relevant for new technologies

Accreditation can take over a year and is expensive. On top of this, there are a limited number of providers. Once a module type has been tested, this is sufficient for the range of modules that use the same cells, primary materials and process. When a 'fundamental' aspect of a certified product range is changed, the test must be conducted again, so it is therefore important to seek accreditation only when the pilot production phase is complete. This is particularly important for flexible modules where any material change such as the active ingredients or encapsulation are considered fundamental and are likely to required recertification.

Figure 24

There are two standards to which PV modules are certified

BS EN 61215/IEC 1215: Crystalline silicon terrestrial photovoltaic (PV) modules; Design qualification and type approval
BS EN 61646/ IEC 61646: Thin-film terrestrial photovoltaic (PV) modules; Design qualification and type approval

Source: Author

Flexible modules cannot and do not have to meet these standards. A new standard for modules without glass is being developed by a number of institutions.

Small PV modules

Small-capacity modules presently on the market are often priced higher than mainstream products by a factor of ten. The highest volume modules are currently priced at US$3-4/Wp, but costs increase as module size decreases because it takes roughly the same time to produce a lower-power module. As production is gauged by Wp output, many major manufacturers do not produce modules of less than 80Wp. As a result, 0.5-5Wp modules can cost more than US$45/Wp; 6-10Wp modules more than US$20Wp; and 10-20Wp modules more than US$10/Wp.

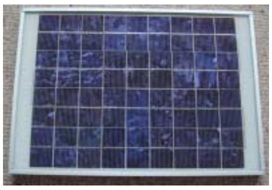


Figure 25

Limitations of small crystalline modules
Susceptible to physical damage (glass front and soft rear)
Expensive
Heavy: glass and metal frame
Shorter life: third-party assembly using lower quality materials.
Larger area/Wp
Limited formats: two cells per 1V, so useable voltages require multiple cells.
Cell off-cuts are often used
Cells are easily broken during assembly

Source: Author

Small modules are often crystalline packaged behind a resin or polymer (not glass) to prevent the use of a metal frame. These modules are smaller and look more rugged but are actually quite fragile. A premium can be charged for thin-film and especially non-glass, more robust formats.

Small modules can cost more than US$50/Wp and crystalline cannot compete in many markets

For an infant technology, low volume production can attract healthy margins while production costs and volumes are improved. There is less need to compete directly on a US$/Wp basis where the PV forms part of a new product for prestige or novel markets. Product uptake is enhanced when these new offerings have inherent advantages such as robustness, flexibility (albeit limited), low weight and good low-light performance. UniSolar, Iowa Thin-film/PowerFilm, Global Solar and Flexcell have followed this approach in recent years.

In the developing world

There are a number of varied benefits for new thin-film technologies that can bridge the gap between pilot and high-volume production.

Conditions favour thin-film in terms of climate and applications

Thin-film should be able to operate at higher temperatures, and must be low cost and simple to use, ie, you don't need to constantly orient them toward the sun to ensure charging.

Mutually beneficial

Thin-film technologies and the developing world need each other. Products with a short lifespan, for example, are still commercially viable. This allows commercial opportunities while still developing the technology for industrialised markets. If developed in a sensitive manner the technology could become a respected brand. Brand in somewhere like Africa is as valuable as it is for industrialised countries, but it can be controlled.

Figure 26

Summary of incentives for thin-film in developing markets

Thin-film does not need to compete on cost and efficiency alone	Success for a given PV technology is usually defined in terms of a production cost and volume (which are interrelated), module efficiency and module operational life. None of these necessarily needs to compete directly with established technology in the developing world.
Volume potential is very high	Huge volume potential for applications such as lighting and phone charging.
Weak competition for high volumes	Although there are hundreds of small PV chargers using crystalline, they are not chosen for brand applications such as phone charging. The PV is simply not suitable. Non-glass thin-film is ideal and its higher initial cost is not prohibitive.
Thin-film will reach the destination	Rugged modules are required to withstand local transportation. A rugged thin-film product with a life of ~5 years is preferred over a fragile crystalline equivalent with a 20 year performance warranty.
Lifetime can be in months for some applications	At present portable energy often means disposable batteries. These will power a radio for, say 10 days. Even if the PV module only has a life of 6 months, this is still commercially viable. Combined with local testing, underperforming product can be returned and analysed or recycled.
Efficiency can be very low and still viable	For PV which is used in or near the home, the physical size is not critical; within reasonable limits. If a phone charger is a square meter but is low cost and works, it will be desired. Efficiency can be developed over time without product redesign.
Brand can be protected while being developed	Brand exposure can be controlled. If the new thin-film product underperforms it can be replaced or recovered without global brand exposure. If it succeeds the process can be used as commercial leverage.
Testing is far easier and quicker	The climate in areas such as central Africa are perfect for developing solar solutions.
Carbon credits for applications such as lighting	Credits are available for offsetting the use of a fossil fuels with a given PV application. Strong examples are small Kerosene lamps and Diesel consumption for larger applications.

Source: Author

Volume potential

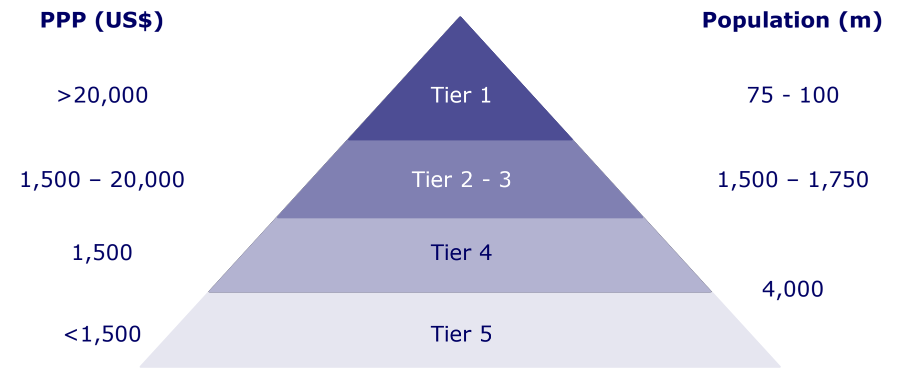
Two billion people, all needing PV

The bottom of the Economic Pyramid[8] consists of the four billion people who live on less than US$2 per day. Of these, nearly two billion have no access to electricity, most of whom live in India, South America and Africa.

Two billion potential users of PV

Figure 27

Economic pyramid for developing world markets



Source: Prahad, C. K. and Hart, Stuart, 2002. The Fortune at the Bottom of the Pyramid

[8] Widely accepted as a term originated by C.K. Prahalad in two papers of 2002, and more prominently in his 2005 book 'The fortune at the bottom of the pyramid'

The World Resources Institute predicts a US$433bn market for energy in its paper 'The Next 4 Billion'.[9]

PV is an ideal solution for applications such as lighting, communications and the replacement of disposable batteries (for radios, torches, etc).

Figure 28

Global distribution of night illumination/mains electricity grids

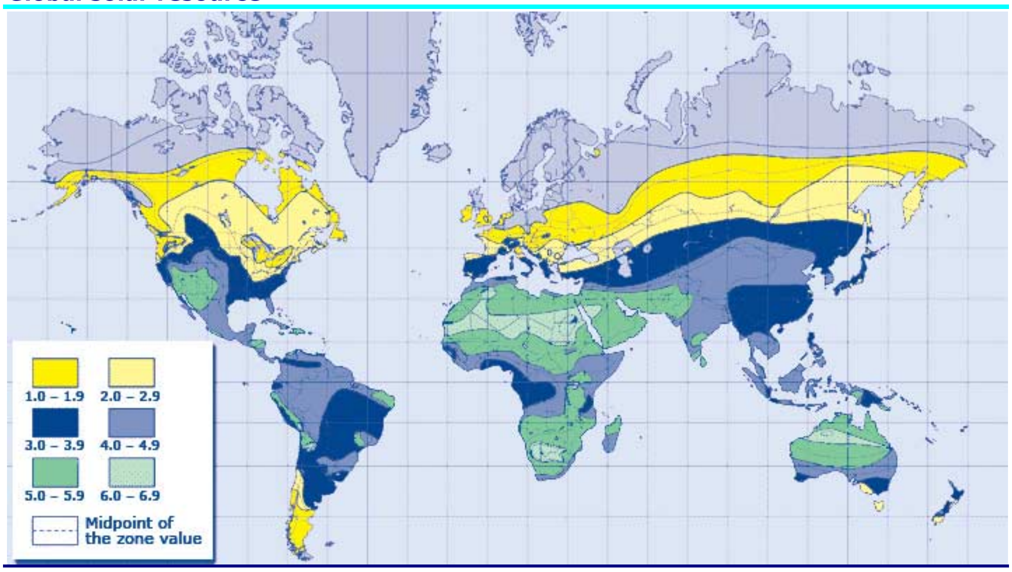
Source: NASA

How fortunate there is a strong sunlight resource

If we compare the distribution of night illumination to solar global resources (Figure 29) the case for PV becomes even stronger because of the relatively sunny climates enjoyed by many developing countries.

Figure 29

Global solar resource



Source: NASA

[9] http://pdf.wri.org/n4b_chapter7.pdf - The total BOP household energy market in Africa, Asia, Eastern Europe, and Latin America and the Caribbean is estimated to be US$433bn, representing the spending of 3.96 billion people

Subsidies for small off-grid systems

Subsidies for grid-connection key to industry development

Residential and commercial grid-connected systems have become dominant in industrialised countries due to subsidy programmes that include capital subsidies, green electricity pricing policies from utilities and service providers, and low interest loans. Equivalent subsidies would probably propel the introduction of small off-grid systems, also.

Off-grid applications in developing countries could benefit from subsidies in the same way as grid-connect has in industrialised nations

Financial incentives for off-grid systems could include carbon credits and micro-finance, while grants for learning, health improvements, rural infrastructure/prevention of urbanisation and for the development of small to medium enterprises could prove to be even more significant drivers. While currently in use, these are not yet employed in combination. However, growth in financial incentives is likely given the significant social, environmental and economic benefits of rural electrification.

Thin-film opportunities

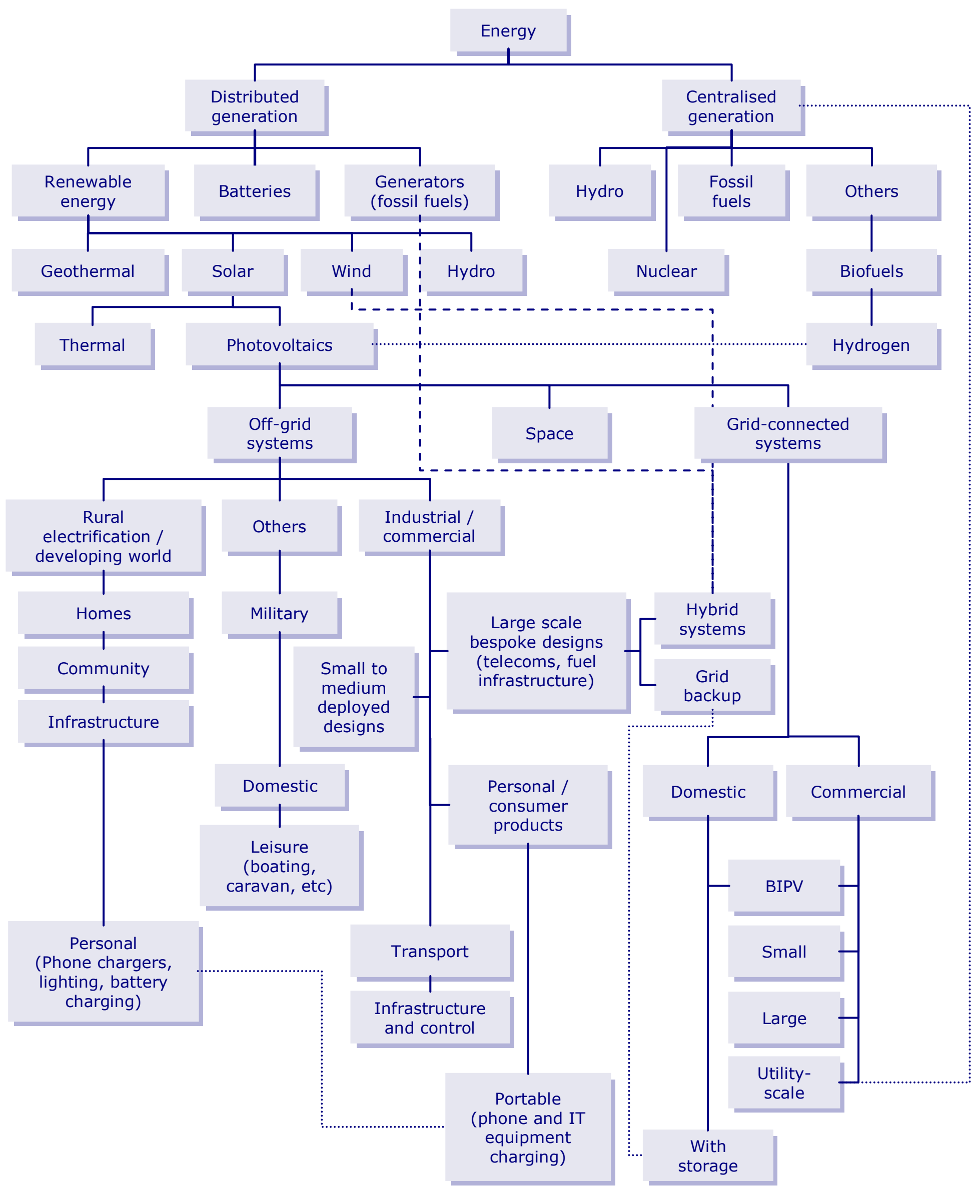
Grid-connected or off-grid; latter neglected for some years now

There are two generic types of PV system: grid-connected and off-grid. Here we concentrate on the off-grid market as this is where thin-film PV has the potential for both volume and profit without significant competition from established technologies.

The evolution of the market

Figure 30

Top-down development of PV



Note: Dashed lines represent existing interactions, while dotted lines represent predicted product or market-share opportunities. Source: Author

The PV focus

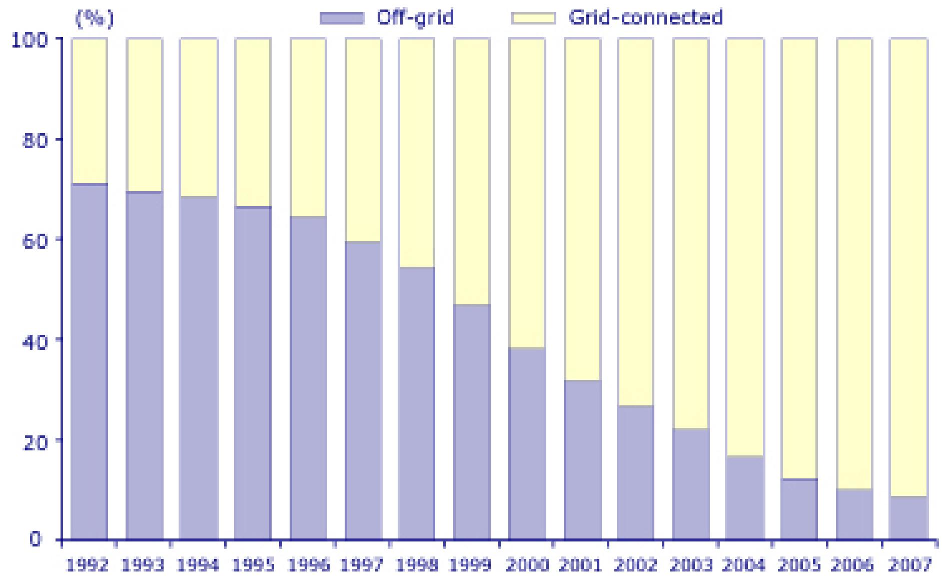
Thin-film technologies are strongest in the off-grid market where smaller modules are required with specific voltages and formats. Unfortunately the off-grid sector has been neglected in recent years, despite its huge potential.

Off-grid used to dominate but manufacturers have steered the industry to their preferred market

The first terrestrial PV systems were off-grid, and most remained so until the late 1990s, after grid-connection legislation was revised. Feed-in tariffs (particularly in Japan and Germany) then directed attention to the grid-connect market.

Figure 31

Grid-connected and off-grid PV power in IEA reporting countries



Source: IEA Photovoltaic Power Systems Programme

Off-grid: Higher user volume, margin potential

Over 1.7 billion people currently live without basic energy services; 80% of them live in rural areas.

Figure 32

User numbers for grid-connect and off-grid applications

(m)	2006	2010	2020	2030
Grid-connected people	5	13	111	450
Off-grid people	10	50	669	1,613

Source: Solar Generation IV - 2007, Greenpeace and EPIA (Moderate scenario)

Everyone in the world could use an off-grid PV solution

Estimates put the number of people using off-grid systems by 2030 at 1.6-2.6 billion, and this does not include portable and consumer electronics PV solutions. If thin-film technologies can be manufactured in sufficient volumes and at low enough costs, one day every person on the planet could find a use for such systems.

On and off the grid

The economics of the two systems are very different. Grid-connected systems are principally driven by the cost of utility electricity. For off-grid systems it is the value of the application being powered and the alternative energy solution for that application; if there is one.

Thin-film must compete primarily on price for grid-connect applications. This is not necessarily the case for off-grid, where functionality such as low-light response, ruggedness, flexibility and versatile electrical formats carry significant value.

Figure 33

Types of PV systems

All PV systems fall into one of these categories

	Electricity grid-connection?	Energy storage?	Market	Typical applications
Grid-connected (Grid-tied)	Yes	No	Urban areas and rural buildings with grid-connections	Homes, offices, commercial buildings
Grid backup (standalone grid-tied)	Yes	Yes	Large uninterruptible power supplies	Areas with unreliable grid performance
Off-grid without storage (standalone without storage)	No	No	Remote location only needing energy during daylight hours	Water pumping, greenhouse ventilation
Off-grid (standalone with storage)	No	Yes	Remote areas or low energy urban applications	Numerous. Remote homes, navigation, telemetry, etc
Hybrid off-grid (standalone hybrid)	No	Yes	Large scale remote industrial	Telecoms stations, oil & gas infrastructure

Note: The term 'remote' is with reference to the mains electricity grid. Remote systems are a sufficient distance from the grid or of sufficiently low energy requirement to make it uneconomical to extend or make a dedicated connection. Source: Author

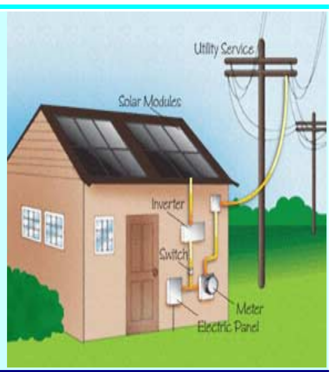
Only operate if connected to a grid and in daylight

Grid-connected systems

Grid-connected systems have no storage capability. They require daylight and must be connected to an active electricity grid to operate.

Installations typically receive subsidies for either the capital cost or for the green electricity they generate, or both.

It is worth noting that grid-connected systems effectively use the grid as a large battery. Excess power generated during the day is exported to the grid. Additional energy required during low light conditions (and of course at night) is drawn from the grid. This is effectively a 100% efficient storage system that can generate income for the user from feed-in tariffs.



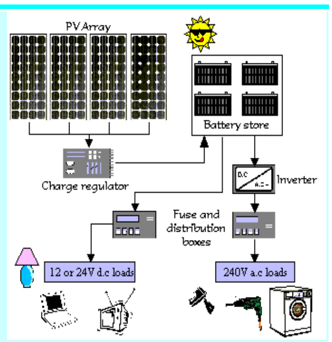
An autonomous power supply that typically charges a battery

Off-grid systems

Off-grid systems nearly always include a battery and are simply standalone electricity generators. In nearly all cases they are the most competitive option for the application. It is rare for off-grid systems to receive subsidies.

The PV charges the battery during daylight hours. The battery is sized not only to supply power though the night, but also during periods of bad weather and through the seasons.

Common applications include solar power calculators, parking meters, telecoms repeater stations and satellites, which nicely illustrates the vast range of potential uses.



Source: Author

Summary of the two largest application types

Figure 34

On-grid and off-grid summary

Grid-connected systems	Off-grid systems
Feeds electricity into the mains grid	Charges a battery
Designed for maximum annual energy generation	Designed to supply load equipment in lowest (winter) daylight
Must be connected to an active electricity grid and be in daylight	24-hour operation
Value lies in generated electricity and, to a lesser extent, carbon offset	Value lies in being cheaper than alternative energy solution (grid, diesel generator, etc)
Cost is proportional to PV capacity	Cost directly proportional to load energy requirement
Subsidies usually required for capital cost, generated green electricity, or both	Rare to receive (or need) subsidies
PV portion of system cost increases with system size	PV portion of system cost increases as system size decreases
High volume PV capacity (Wp)	Low volume PV capacity (Wp)
Modules 80Wp to >300Wp. Large/high power modules often improve economics	Single cells to around 150Wp modules
Module voltages of ≥24V to >100V 'grid-connect modules'	0.5V to 24V 'off-grid modules'
System capacities around 1kWp to >50MWp	System capacities <0.1Wp to around 30kWp
High efficiency low cost modules dominant	Small crystalline modules dominant, though thin-film preferred, especially rugged formats
Modest margins for module manufacturers	High-margin potential for module manufacturers
Market potential being realised	Market in infancy with enormous growth potential

Source: Author

Grid-connected: Reducing cost and carbon emissions

Grid-connected systems purchased to reduce energy cost and emissions

The primary reasons for installing PV systems and connecting to the utility grid are energy cost savings and, to a lesser extent, carbon emission reductions. The notable exception to this is Building Integrated PV (BIPV), which we describe below. While there are numerous other benefits - increased property value, carbon credits, brand enhancement, PR - these rarely justify the capital investment on their own.

Figure 35

Governing factors for grid-connected systems

Cost	The principal concern for most purchasers. The capital expenditure is justified against the total electricity generation over the life of the system. Module performance warranties are therefore crucial.
Energy requirement	A customer may wish to generate a percentage of their energy consumption from the PV system. This is particularly true for small commercial buildings and some domestic homes.
Space availability	Limited roof area (or limited visible roof area) may define how much PV is installed. This in turn defines the cost and capacity of the system, depending on the PV technology.

Source: Author

Figure 36

Summary of PV for grid-connect markets

	BIPV	Domestic	Small commercial	Large commercial	Utility scale
System capacities	~100sWp to a few kWp	1kWp to ~5kWp	~3kWp to 10s of kWp	~100kWp to a few MWp	~>a few MWp to <100MWp
Efficiency requirement (space constraints)	**Medium** Value is not just in the generated electricity	**Medium** Cost is most important but space is often limited so >10% has to be used		**Medium** Roof space is often available so a-Si can be used (~6%)	**Medium** Cost far more important, though lower efficiency requires more module infrastructure
Life requirement	**Medium, >10 years** BIPV volumes are low and so warranties are sometimes shorter.	**High, >20 years** The longer the performance life, the more money is saved/generated by the system		**Very high, >25 years** Performance warranties define energy payback and operational revenue.	
Ruggedness requirement (non-glass modules)	**Medium** Flexibility offers more design options	**Medium** Would be used if cost and efficiency were the same as glass modules.		**Low** Systems are on rooftops or in remote/protected areas.	
PV module sizes	~10Wp to >200Wp	~60Wp to >200Wp		~100Wp to >300Wp	~70Wp to ~200Wp
Electrical formats (typical)	Wide range, typically >12V	~24V to ~60V		~40V to >70V	
Special requirements on PV	Visual aspects often very important	Must allow mounting to roof - usually meaning it has a metal frame		May be assembled at site to save cost	
Value to PV manufacturer	**Low** Though good PR	**Medium** Brand is growing in value as competition increases		**High** A large project can require the same PV as a distributor will use in a year	**High** Complicated contractually, though PV volume can aid expansion of production
Module volumes	**Low** 10s to a few 100 per system	**Low** 10s of per system	**Low** 10s to a few hundred per system	**High** 100s to low 1000s per system	**Very high** >50,000 per system
Margin potential	**Low** Small volumes mostly and competing with cheap passive materials	**Low** Relatively long supply chain.		**Medium** High volumes but increasing competition as supplier capacities continue to grow.	
Preferred technology Reason	**Crystalline** Cost and availability	**a-Si or polycrystalline** Cost, energy yield, though space can be limited		**a-Si** Cost. Assuming space is available.	**Crystalline** Long warranty and cost at volume.
Status of market	Understood, though small due to cost	Erratic due to government support requirements. Still has lots of potential		Healthy. Corporates using PV within CSR and environmental plans	Growing as PV production volumes increase and costs reduce.

Source: Author

Many variables determining opportunity

The potential success of each technology and each market are interconnected. We present a guideline for the next two to five years in Figure 37. Thin-film technologies are not sufficiently mature to have a track record. This table assumes efficiency, cost and volume will reach levels widely predicted by the industry at this time. Significant advancements such as with CdTe from First Solar will change the balance shown.

The potential for thin-film in different applications

Figure 37

Thin-film potential for grid-connect

	BIPV	Domestic	Small commercial	Large commercial	Utility scale
Glass					
a-Si	**Low** Limited suppliers = high cost	**Low** Space typically limited	**Medium** Where space is available. Will lose out to other technologies in time		**Low** CdTe already cheaper and more efficient
CdTe	**Low** Limited production	**Low** Acceptance of cadmium a barrier	**Low** Limited supply and acceptance of cadmium	**High** Presently limited supply, but low cost	**High** Low US$/Wp crucial, modest efficiency acceptable
CIGS	**Low** Limited production		**Medium** If volumes increase. Life and cost must compete with crystalline		
DSSC	No volume commercial production				
Flexible					
a-Si	**High** Metal & PVC roofing	**Low** Cost & limited applications	**Medium** Metal & PVC roofing		na Flexibility not needed.
CIGS, CdTe, mc-Si	**Low** High cost and limited formats	**Low** Cost uncompetitive, limited volume. Higher prospects over longer timescales			na
DSSC/OPV	**Low** Cost, life & volume not proven			na	na

Notes: na indicates that it cannot compete with alternatives within at least the next five years. Source: Author

Building integrated

BIPV will remain a small market until cost is significantly reduced and architects widely accept PV

Building integrated PV (BIPV) forms part of the building envelope, rather than simply being 'bolted on' to the existing structure. In theory, any PV technology can be integrated into a building. Thin-film can be more readily produced in non-standard formats and will compete directly on cost with crystalline. The present high cost and low volume is limiting uptake.

The principle is to replace a standard construction material (such as a roof tile or cladding panel) with an equivalent that includes PV, not only generating power, but performing additional functionality such as weather protection, heat insulation, noise insulation, sun shading and safety. These can have challenging design requirements. Growing environmental awareness means architects are increasingly using BIPV as a design feature. This is especially true for organisations that want to be seen as 'green'.

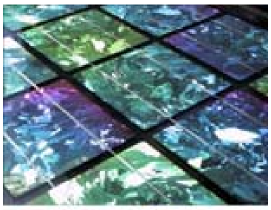
Figure 38

Summary of the BIPV sector

Typical locations	Sunnier climates are far more favourable, especially with high diffuse light. Shading must be avoided and this seriously limits installations.
Mounting and integration	The most common formats are roof tiles and shingles, façade panels, rain screen cladding, glazing systems and louvers. These are most commonly employed in commercial buildings and domestic properties (roof tiles).
Economic drivers	Substitution of expensive decorative materials such as marble with PV. A public expression of a company's environmental commitment. Legislation requiring a building to generate energy on site is becoming more widespread. Although BIPV is not the cheapest way of achieving this, its additional benefits make it a viable option for some. BIPV is more cost effective for new builds, expansions and major roof and/or façade renovations.
Barriers	Cost and integration issues. BIPV panels can be two to ten times more expensive per Wp than a standard module. In addition they are often replacing very cheap building materials such as glass and roof tiles. There are significant design requirements of not only the panel integration but also cable routing, electrical system housing and mains connection.
PV technology	Standard module formats are difficult to use. Crystalline cells however are dominant for cost reasons. Formats include: Laminates for roof tiles; glass-glass (standard crystalline cells between two sheets of glass); semi-transparent modules; and coloured modules (see below). BIPV modules are produced at significantly lower volumes than standard products. This can lead to availability issues.
Crystalline modules	Standard crystalline modules have limited applications and are not the most attractive visually. However, they are often the most cost effective approach. They are only used for façade cladding or with specially designed roof integration systems that accept standard panels. Most crystalline suppliers are steadily increasing the physical size of panels but these larger formats are often less suited to integration.

Source: Author

Standard crystalline cells are most commonly used in BIPV module products due to cost. Some companies specialise in BIPV formats such as transparent cells (Sunways & Ertex Solar), glass-glass modules (Saint Gobain, Solarnova, Solon, Scheuten Solar, GSS), acrylic plastic modules (Sunovation) and coloured cells (multiple crystalline manufacturers).



Coloured cells

Crystalline cells are blue or dark-blue to black due to the anti-reflective (AR) coating. By varying this green, gold, brown and violet can be created. Efficiency is reduced (by 10-40%) and the cells are more expensive due to limited volume production. Coloured cells can suffer from variations in exact appearance. This can result in a patchwork effect, even within a module. Selection of coloured cells is therefore very important but also adds cost.

Nearly any crystalline cells from the major manufacturers can be coloured. Suppliers, such as RWE Scott Solar and Ersol Solar Energy AG, can provide small quantities of cells for high-profile small projects.

Transparent solar cells

Using transparent PV is very expensive compared to glass. A one-square-metre pane of glass costs roughly US$10, whereas PV may cost more than US$200 and the associated costs of wiring and grid-connection are often prohibitive.

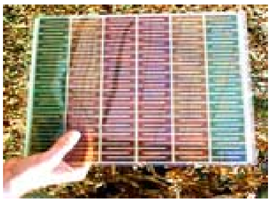
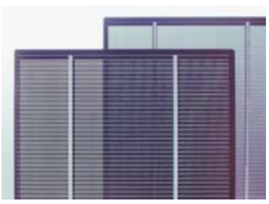


Figure 39

Thin-film and BIPV

Existing BIPV products such as roofing tiles can accept thin-film	Many products such as roofing tiles and cladding panels are designed to accept a frameless laminate of, at the moment, crystalline cells. A thin-film equivalent can be substituted without significant product redesign, if any. The PV must be produced with the required dimensions and electrical parameters.
Transparent and coloured products (such as DSSC) are not as valuable as suggested	Transparent PV modules are presented as a major potential for windows, shading panels, atriums, etc. DSSC, OPV, a-Si and even crystalline can be produced with transparency. DSSC is marketed for its availability in different colours and/or varying transparency. Not only have these markets proven very small but limited DSSC volume is more expensive than alternatives. The efficiency of DSSC declines with colour alteration - from around 5% (about the same as transparent a-Si) to <3%. It will therefore be many years before DSSC or any other thin-film technology gains a strong commercial position from these features.
Low cost PV still has the same system component costs	If grid-connected, the cabling must be routed inconspicuously and an inverter and associated electrical equipment is required to allow grid feed-in. The level of energy generated is low (due to lower PV efficiency and location) which increases the system installed cost per peak watt of PV.
Better temperature stability	An area of particular concern for roof tiles and other formats where air circulation is limited. Crystalline PV efficiency declines as temperature increases. Thin-film is far more stable, resulting in higher energy yield from a given capacity.
Better low light response	Locations are often not ideal and thin-film will generate more from diffuse light.
PV energy must be efficiently converted for the grid	Thin-film is promoted as having a higher energy yield per installed capacity. This is true though it needs to be effectively converted to supply to the grid and many inverters are inefficient at low energy capacities. An inverter may operate at <50% for lower light conditions. At very low light levels it may not convert any PV-generated energy. The actual energy fed to the grid from thin-film will therefore not be as superior to crystalline as some proclaim.
Warranties are not always as substantial	BIPV module warranties are not always as long as their standard counterparts.

Source: Author



Transparent mono or poly-crystalline cells are produced by etching away active areas or by forming tiny holes in the cells during manufacture. Transparency can be 1-30%, but is typically 10%, though the reduction in efficiency is generally greater than this. This also costs roughly twice as much. Suppliers include Sunways and Ertex Solar.

Transparent amorphous silicon modules are produced by laser etching away active material. Transparency is typically around 10%, but they also suffer from a disproportionate loss of energy and increased cost. Suppliers include Solon, Sharp and Kaneka.

Smart home control systems (such as Z-wave, Insteon and ZigBee) offer numerous applications for indoor PV such as environmental monitors and controls, sensors to detect outdoor conditions and occupants, blinds to control passive heating and cooling, appliance standby control, etc. Smart tags (RFID), supermarket price tags and other consumer-focussed applications represent huge potential value.

Indoor PV has great potential, though not until a technology is available in the right formats

Figure 40

Indoor BIPV

Pros: The market potential	According to sources such as Global Industry Analysts the world home automation market is set to witness robust growth and reach US$2.4bn by 2010. In 2008 the value of the entire RFID market will be US$5.29bn, up from US$4.93bn in 2007 according to a 2008 IDTechEx report. PV will not be applicable to many applications within the overall market but, if cheap enough, can add value to several areas.
Cons: Cannot 100% test PV and energy capture development required	Need to produce PV in very small sizes, though the value is often higher than larger modules per Wp. Consistency of PV production is paramount as it is not practical to test each small module. The generated energy levels are very small (micro amps) and are not easily captured and stored. Development in high-efficiency battery charging systems is required.
PV technology	DSSC and OPV will operate in artificial and very low levels of light. Amorphous silicon can be 'tuned' to be more sensitive to artificial light, though as a result is damaged by strong sunlight.

Source: Author

Domestic applications

With installations of PV on domestic properties now widespread, mounting systems and BIPV products are available that allow PV to be used with a huge range of building and roofing types. The installed capacity is usually only a few kWp and nearly always supplied by a relatively small systems integrator rather than a module manufacturer.

Building-integrated or mounted domestic installations are small and provided by systems integrators

Installations are building integrated or building mounted. The most cost-effective and therefore most common form is standard crystalline modules mounted on a frame above the existing roof. BIPV roofing tiles slates and shingles are popular, but more expensive, even for new building projects.

Figure 41

Domestic sector summary

Typical locations	The sunnier the location, the better the payback. Urban, suburban and rural areas without structural shading (tall buildings or trees) are typical.
Mounting and integration	Installation is nearly always on the roof. The roof area which best faces the equator will generate the most energy. However tilt angle and shading from roof features are important.
Economic drivers	Grants and/or feed-in tariffs are usually required. Increased property value is sometimes sited, as is the value of offset carbon. For new build projects, BIPV can be incorporated at lower costs whilst still being eligible for grant funding. There are generally no planning permission issues.
Barriers	Cost. Even with modest supplier margins on the equipment and low cost installation solutions, PV is expensive. If a domestic home owner wishes to spend money to reduce their electricity bills and/or carbon emissions, green utility electricity, energy efficiency measures and solar thermal are all cheaper options than PV. A survey of the property is required before an accurate quotation can be made. Grant applications and final certification are also required.
PV technology	Polycrystalline is the best compromise between efficiency and cost and is therefore in widespread use. The cheapest modules available (with a long warranty period), tend to be amorphous silicon on glass. The technology is also desired for non-idea orientations where it can still produce valuable levels of energy. However the lower efficiency means greater surface area requirement and this is prohibitive.
Crystalline modules	A significant proportion of the market, though system capacities are typically only a few kWp. System installers and integrators are often quite small businesses. Purchasing a limited range of modules to serve the whole range of their customer base is important for cost reasons. Crystalline suppliers tend also to offer a greater range of module capacities.
PV manufacturers	Are becoming more concerned with brand. The industry is focused on grid-connect systems and competition is fierce. Manufacturers are looking for ways to associate their brand with the home owner - without having to take the burden of dealing with them. Some have partnered high street retailers (such as Sharp teaming with Currys in the UK), some restrict distributors from carrying other brands, and some have partnered with utilities.

Source: Author

Figure 42

Opportunities for thin-film in BIPV

BIPV potential, though cost is high	As previously described, thin-film has potential for incorporation into existing BIPV products.
Lower costs will aid growth	Cost is a major advantage though must be married with warranties comparable with crystalline (>20 years)
Warranties must compete	Warranties are essential for payback. If the warranty is shorter, the capital cost must be proportionally lower.
CdTe acceptance	Cadmium Telluride may not be popular due to public perception of the hazards of Cadmium
Better low light response	Compensates for lower efficiency. Local shading has a greater effect on crystalline, which reduces energy output.
PV energy must be efficiently converted	Low light PV efficiency must be married with low power electricity conversion efficiency to capture value
Limited roof area	As shown in the table below, efficiency is important. It highlights why CdTe and CIGS may not be suitable for all installations.

Source: Author

Roof area is limited for domestic applications. A typical home in Europe requires around 3,000kWh/year of electricity and while sunlight energy varies, a 3kWp system is generally sufficient. Figure 43 shows the increased area requirement for lower efficiency technologies.

Figure 43

Area requirement to supply a typical domestic home

		c-Si 14.0%	**CdTe 10.5%**	**CIGS 9.5%**	**a-Si 3-jnc 6.5%**	**a-Si 1-jnc 5.5%**
3kWp						
Area required	m^2	21.4	28.6	31.6	46.2	54.5
	ft^2	230.7	307.5	339.9	496.8	587.1

Note: Minimum area requirements are shown, mounting and installation specifics may increase array size. (1 square metre = 10.76 square feet) Source: Author

Small commercial: PR function

Systems installed by third-party integrators, similar to domestic; PR value and CSR can influence uptake

The term 'small commercial' can apply to both the installed capacity and the building sizes to which the PV is installed. Installations ranging from a few hundred watts to several kWp are common. The energy generation is not always paramount, as visible PV systems can fulfil a PR function, 'demonstrate' a green commitment or provide an alternative architectural feature.

Displays are often used, especially if the PV system itself is not easy to see, and can be located in a reception area to show present generation, cumulative generation and, often, carbon savings.

Figure 44

Opportunities for thin-film in small commercial systems

Similar to the domestic market	Small commercial projects carry the same opportunities as domestic. Systems are often larger and therefore more attractive.
Brand association	Alliance with a known consumer or high-street label is of value.

Source: Author

Figure 45

Small commercial sector summary

Typical locations	Sunnier locations for optimum energy generation are more important to commercial organisations than to homes. Large cities create significant shading issues so high street shops and offices are not always suitable. Fuel filling station roofs are ideal locations, as are many business and retail park buildings. Vertical walls with good sunlight resource are attractive. There is a greater requirement for visual installations, often at the expense of energy generation.
Mounting and integration	Roof mounting similar to domestic installations; including fuel filling stations. Office buildings and atriums place more value on the visual impact of the system. This is the most prominent market for BIPV.
Economic drivers	Feed-in tariffs, grants and other funding from sources such as local authorities is important. Several internal budgets can collectively fund the installation such as CSR, marketing, PR, maintenance and energy. An identified load such as lighting or computers within the organisation can drive an energy generation requirement for the PV.
Barriers	Cost is a major issue, especially given that the most effective systems are likely to be unseen roof-mounted formats. As for homes, PV is not the cheapest way to save electricity or reduce carbon emissions. Buildings in cities or developed estates often suffer shading issues, which further increases the cost of the PV-generated electricity. Money spent on alternative "green" measures may have a greater impact. Commercial offices and retail outlets typically consume far more energy than domestic homes. A given PV capacity therefore makes a smaller contribution to energy consumption and carbon emissions.
PV technology	BIPV is popular if budgets allow for it. For roof-mounted systems polycrystalline tends to offer the best trade-off between cost and space requirements; as for domestic installations.
Crystalline modules	Similar to domestic applications. Modules are used extensively and crystalline cells are common in BIPV.
PV manufacturers	As with domestic installations, manufacturers are keen to place their brand in the public domain, though do not often work with the end customer for this scale of installation.

Source: Author

Large commercial: Favoured by suppliers

Large system can require as many modules as a systems integrator purchases in a year

Terminology varies, though installed capacities from 100kWp to a few MWp are typical of this category. The lower capacity systems are installed on buildings with large roof areas, while the larger capacities are often purchased by corporations and national organisations and installed over a site or complex. In both cases a number of smaller arrays may form the overall capacity. It is rare for these systems to be ground mounted or installed on sloping roofs.

Many manufacturers have developed integration systems specifically for their technology. These include UniSolar for metal roofing and SunPower (Powerlight) using glass modules. Global Solar's new PowerFlex Solar Strings is one of the first non-glass examples for integration into roofing products.

Figure 46

Opportunities for thin-film in large commercial systems

Lower cost than a-Si	All the present benefits of a-Si can be transferred to an alternative if efficiency is higher and/or price is lower. Warranty must be competitive.

Source: Author

Figure 47

Large commercial sector summary

Typical locations	Roadside noise barriers are a popular application, albeit underutilised.
Mounting and integration	'Industrial sheds', distribution warehouses and other large building with flat roofs. Facilities which have low energy consumption, large roof area and are in a sunny location are ideal candidates. The larger the system the more likely it will be optimally tilted and oriented towards the equator.
Economic drivers	Feed-in tariffs are nearly always sought, particularly in the form of long term agreements with the utility. Grants from local authorities, governments, regional development agencies, etc, are sought and often available. Where energy consumption of the facility is low, the system can reduce or even cover running costs for the life of the PV. PV installations can be eligible for capital allowance tax savings.
Barriers	Weight of the system and fixing requirements can affect roof life and insurance of the building. Roof load capacity and the building's existing electrical connection to the grid can limit the scale of the installation. Installed by large systems integrators, these systems are a major electrical and mechanical undertaking.
PV technology	A strong market for amorphous silicon glass modules due to low cost, space availability and energy yield. However large flat roof space does allow optimum orientation, which reduces the advantage of a-Si, especially in sunny latitudes. Quantity of modules can be a reason to use alternatives, though the PV itself is often a more significant section of the overall cost. For higher capacity systems, manufacturers are more likely to reduce prices (slightly), especially if good PR is involved.
Crystalline modules	A favoured market, though large areas allow cheaper lower efficiency a-Si. Some manufacturers produce large modules (>250Wp) for this market (such as SunPower).
PV manufacturers	This is currently the favoured market of suppliers, though is increasingly being overshadowed by utility scale installations. A large system can require the same quantity of modules as a distributor may require in a financial year.

Source: Author

Utility scale: Economics becoming more favourable

VLSPV is favoured by manufacturers as scale can justify production capacity investment

Also termed very large scale PV (VLSPV), until recently these systems were categorised as more than 1MWp, though now over 10MWp is more realistic. This is the only application of PV that does not utilise the distributed generation advantages of the technology. These are (relatively small) alternatives to traditional fossil fuel and nuclear central generation but have significant potential[10].

Only a few years ago 1MWp systems were 'very large'; Now a 100MWp system is close to reality

In 2003, 1MWp PV systems were a rarity, but by mid-2007 there were 150 systems larger than 1MWp operating around the world; with several over 10MWp. The race for the first operational 100MWp installation is likely to be over by the end of 2009.

With high efficiency and high capacity modules, fewer electrical connection and mechanical fixings are required for a given capacity. When employing tens of thousands of modules this becomes very important.

[10] One third of the land area of the Earth is dry desert, using about one-thirtieth of it for photovoltaics could cover the total world energy consumption.

Cost dominates, though module capacity becoming key factor

Figure 48

Module quantity and area requirement for example PV technologies

	SunPower m-Si	Kyocera p-Si	Sharp p-Si	First solar CdTe
Module Wp	210	205	170	75
Module area	1.20	1.49	1.31	0.72
10MWp				
Modules required	47,619	48,780	58,824	133,333
Area required				
M^2	57,143	72,683	77,059	96,000
ft^2	615,081	782,353	829,454	1,033,335

Note: Minimum area requirements are shown, mounting and installation specifics may increase array size. (1 square metre = 10.76 square feet). Source: Author

Figure 49

VLSPV sector summary

Typical locations	The sunniest locations on Earth, often deserts. Installations are particularly favoured near to where energy demand is growing rapidly (such as the Gobi desert in China, or the Thar desert in India, or the Southwest of the United States.)
Mounting and integration	These systems are always ground mounted and installed at optimum tilt angle and orientation to the sun.
Economic drivers	Feed-in tariffs offering a premium for the clean energy being generated are almost essential. Land is easy to find and relatively cheap. Installations can be modular with output capacity increasing over time. Social-economic benefit for some of the poorest areas of the world can be a strong motivator. Installation sizes are ever larger as economics become more favourable in the face of increasing fuel (and therefore grid electricity) costs, climate change and lower PV costs to name but a few.
Barriers	Locations mean transmission infrastructure is required (as for offshore wind farms). Local water and energy requirements for construction must be implemented. Energy will need to be stored if PV contributes significantly to the overall generating capacity (at present air conditioning loads in particular marry well with generation in the heat of the day).
PV technology	The PV represents a large percentage of the overall costs. The cheapest technology will therefore be selected (for a given operational life, ruggedness and environmental stability). Concentrator systems are aimed at this market. However these do not yet exist at the scale or volumes necessary. Long operational life of the module is critical, as is the ability to withstand the extreme heat of these locations.
Crystalline modules	Are most commonly used due to their long (warranted) operational life. However, cheap thin-film technologies are starting to take a share in the market. A 40MW CdTe (First Solar) plant is being installed in Saxony, Germany and will be completed in 2009.
PV manufacturers	Producers obviously favour these installations in principle, particularly in terms of financing new manufacturing capacity. There is increasing competition as more manufacturers are capable of supplying these module quantities. Project timescales are long and the process is complicated. The design, installation and maintenance are conducted by dedicated project management organisations. As system sizes grow, on-site module production/finishing facilities and other dedicated plant is being implemented.

Source: Author

Figure 50

Opportunities for thin-film in utility-scale systems

Cost initially, though efficiency must follow	First Solar has demonstrated that low cost (with a competitive warranty) wins these large systems. However, due to the volume of modules involved, as more efficient technologies achieve lower cost they will be preferred.

Source: Author

Off-grid: Charged and ready

Off-grid is about charging batteries and thin-film is more easily configured than crystalline to do this

Off-grid applications require PV modules that can charge batteries at 12V and lower, whereas grid-connection typically uses modules at more than 24V. Since crystalline PV is expensive to produce in small formats and is not ideal for most off-grid solutions, this market has been largely overlooked in recent years. In contrast, thin-film is already proving itself viable since it is more readily produced in smaller module sizes. When non-glass modules become available in high volume and/or at low cost, we could see a paradigm shift in the PV industry in terms of target markets and applications.

Wide margins possible as cost of alternative is often far higher than PV

Wide margins are on offer since the value of an off-grid system derives from the value of the equipment it powers and the cost of alternative energy solutions; if there are any. Satellites are an extreme example of the economics with no alternative energy source meeting the requirements of the application. Off-grid systems have been the preferred energy solutions for many industrial applications for decades. Since they are economic, they are rarely subsidised.

PV system cost is directly proportional to the energy requirement - unlike most electricity generators

Off-grid system costs are directly proportional to the energy requirement (for a given location or region), so a more efficient final application device means a cheaper solution (unlike other generators). The most striking example is LED lighting: A rural amenity light costs more than 10 times as much to power as an LED equivalent.

Figure 51

Summary of PV for off-grid markets

	Large bespoke designs	Small to medium scale deployed designs	Portable and consumer electronics
System sizes	~>500Wp-20kWp	~1Wp to ~500Wp	~0.5Wp to ~20Wp
Efficiency requirement (space constraints)	**High** >10%	**Medium** >10% preferred, though not the most important factor	**High** As high as possible, though not the most important factor
Life requirement	**High** >10 years	**Medium** ~5-10 years	**Low** ~2 years
Ruggedness requirement (non-glass modules)	Low (though preferred)	Medium. (preferred, sometimes essential)	High. Essential for high volumes.
PV module sizes	80Wp to 150Wp	1Wp to 150Wp	0.5Wp to 60Wp
Electrical formats (typical)	12V, 24V	12V, 6V	5-6V, 2-3V
Special requirements on PV	None	Ambient light response, rugged and small size preferred	Ambient light performance, rugged, light weight, size, volume must be available
Value to PV manufacturer	**Low**	**High**	**Very high**
Module volumes potential (annual)	**Low** >1 million	**Medium** >100 million	**Very high** >1 billion
Margin potential	**Very High** >100%	**Medium** >50%	**High** >100%
Preferred technology	**Crystalline**	**Non-glass, low cost**	
Reason	warranty, efficiency	Vandalism, ruggedness, product price point	
Status of market	Mature (>40 years) and advancing with new user technologies	Young (<15 years). Growing rapidly	Infancy. No available technology to meet required of cost, volume and ruggedness

Source: Author

Energy efficiency advancements can drastically increase the value of a PV solution

As digital electronics become more energy efficient (due to battery limitations) it becomes more viable to power them with PV. And, with the implementation of energy-efficiency legislation (manufacturing and regional), more and more equipment can be powered cost effectively off-grid.

Figure 52 is a generalisation, but does offer insight into the major factors for off-grid technology. Where potential is stated, this assumes an appropriate PV module solution is available. There are a huge range of variants, though it is useful to outline the four broad categories shown.

Market potential is dependent on the PV product. Modules of the ideal size (physical and electrical) must be produced in high volumes (millions) to satisfy the mass-deployed design and portable markets. The growth of these sectors has been limited by available technology formats.

Figure 52

Opportunities for thin-film in off-grid markets

	Large/ industrial	Mass-deployed designs	Portable & consumer	Rural electrification/ developing countries
Glass				
a-Si	**Low** Limited space/cost of array structure	**Medium** Best cost/efficiency compromise at present	**Medium** Flexible taking market as costs reduce	**Low** Flexible required. Crystalline dominant (though not desired)
CdTe	**Low** Low efficiency and limited formats	**Low** Limited formats & available volume. Cadmium an issue		**Medium** Cadmium not desired but cost very important
CIGS	**Medium** If cost <crystalline with same life	**Medium** If formats were produced at reasonable volumes		**High** Must be cheaper than crystalline
DSSC	No volume production, a-Si cheaper			
Flexible				
a-Si	**Medium** Vandal resistance carries a small premium	**High** Huge demand. As costs reduce, markets will mushroom. Limited volume and formats at present		
CIGS, CdTe, mc-Si	**Low** Unproven life, limited formats, cost			
DSSC/OPV	**Low** Life requirement	**Medium** Life must be ~>5 years	**Medium** Volume must be high	**Medium** Not fixed locations due to life

Source: Author

Application sectors in Appendix 4

Also see Appendix 4 for a summary of off-grid sectors and example applications.

Figure 53

Systems design - Primary considerations

Energy requirement	The *daily* amount of energy required by the load equipment
Location	The amount of sunlight energy available at the location of the installation (figures published by NASA and others)
Energy reliability	Battery autonomy and overall spare capacity of the system

Source: Author

Recharging batteries

Nearly all off-grid systems charge batteries. However, battery requirements for PV systems are quite different from traditional methods of use in terms of how they are charged, discharged and the conditions they are required to operate under; particularly the effects of temperature.

Matching PV with appropriate battery can drastically improve a given solution

If thin-film technologies can be designed to work with carefully selected batteries, product performance could double for the same amount of PV capacity.

Battery technologies and their specific use within PV applications is a huge issue and one that cannot be adequately covered within this report.

PV solutions could (and should) replace disposable batteries

To many it is incredible that disposable batteries remain the default energy solution for portable equipment that requires the user to fit the battery. Many argue that disposable batteries should not be available at all. They are expensive, require up to 30 times the energy to produce than they deliver, and are very damaging to the environment. There are a huge range of battery technologies and types, though by their very function they all require chemicals and materials that we would rather not be using. PV, enabled by thin-film technologies, can replace the use of disposable batteries in a high number of applications.

Tailored electronics can also dramatically improve the value of PV

Electronic solutions which allow the capture of small amounts of PV-generated energy to be stored in a battery are also increasing the range of applications that can be cost-effectively charged using PV.

Large bespoke designs

The most reliable form of electricity available – and often the cheapest option

Each system is designed for the specific location, application and equipment being powered. Design and equipment principles are transferable, though it is rare for two systems to be exactly the same. Systems range from a few 10s of watts to 10s of kilowatts with an operating life of 10-30 years.

Figure 54

Opportunities for thin-film in large bespoke projects

Efficiency must increase	Opportunities are small. Space is limited and modules with good low light conditions are not as critical. However, if they are similar in cost and efficiency to crystalline they will be used. Long warranties of more than 20 years are essential.
Large projects waiting for thin-film	There are a number of very large projects for which thin-film could be used. For example telecoms companies such as Ericsson have or are installing more than 20,000 base stations. If cost is low enough a partnership agreement would lead to high volumes (around 15kWp per system.)

Source: Author

Figure 55

Large bespoke sector summary

Typical applications	Telecom base stations, oil and gas infrastructure (offshore platforms, pipeline corrosion-protection, safety systems), rural electrification (schools, hospitals, community buildings), central village power stations, irrigation and desalination systems.
Location	Remote from the mains grid, which is costly to extend. Often located in areas difficult or expensive to reach, preventing the use of diesel generators, which need maintenance and regular fuel.
Economic drivers	High margins; often more than 100%. The cost of an alternative power solution may be several times higher. Reliability and very low maintenance is valuable. (These systems are the most reliable form of electricity supply available (when correctly designed)). Long life (batteries can last 10 years, the system 30 years) and system cost is optimised for the user requirements (unlike other generators).
Barriers	Poor design results in poor performance and discourages potential customers. Modules must be 12V or multiples thereof and volumes are low. This results in higher costs and lower availability. Specialist suppliers are not common as systems require design prior to quotation. They also have complicated customer specifications and long contract timescales (months to years).
PV technology	Crystalline is preferred. Space is often limited and mounting structures for the array can be costly, so the higher the efficiency, the smaller the array. Life is also crucial. These systems are typically designed for more than 15 years of operation.
Crystalline modules	The first application for crystalline and the reason commercial modules were developed. However newer grid-connect modules with higher voltages and power ratings are not suitable. Crystalline will continue to dominate until an alternative is available.
PV manufacturers	Module volumes are low and so the sector is supplied by third-party distributors. Module cost is typically 50-20% of the total.
Additional	Hybrid PV systems are often used for larger loads. A PV-diesel generator or PV-wind generator or a combination of all three can improve the economics for a site. In the case of diesel, the PV is sized to reduce the operating hours of the generator, thus increasing maintenance and refuelling intervals.

Source: Author

Small/medium scale deployed: Hundreds of opportunities

Thin-film could make its name in this sector

This type of PV solution is not about supplying energy, it is about providing a function. Whether it is a lighting solution, night-time advertising or 24-hour communications, these all need to be easily deployed, have low operational costs and sufficient life to allow commercial viability.

Thin-film technologies are far more effective in ambient and indirect light conditions. For a given product this means the PV does not need to be oriented and inclined for optimum sunlight conditions at each installation site - as is the case for crystalline technologies. This removes the need for skilled installation and allows a single or limited number of system designs to cater for a large number of locations within a desired application. This is especially valuable in regions where specific site conditions can vary, such as cities.

As with larger bespoke systems, the markets for these systems are sometimes segregated into off-grid electrification and industrial off-grid.

Figure 56

Small/medium scale deployed sector summary

Typical applications	Street lighting, parking meters, road signs, road-side phones, monitoring devices (air, water, noise, temperature, humidity, etc), navigation (marine, airfield), utility infrastructure (monitoring, safety and remote control), rural electrification - domestic and small commercial (lighting, refrigeration, communication, entertainment), safety and security, solar home systems (SHS).
Location	Historically only in rural areas, though now these systems are everywhere; urban and rural, developing and industrialised countries. There are very few locations on the planet where these systems do not have a viable commercial application.
Economic drivers	Energy requirements of the load equipment are too small to justify a grid-connection and life requirement is too long for battery power alone. Energy-efficient equipment such as LED lighting, digital electronics and communications has massively increased viable applications. Electrical load is typically known, allowing optimised cost.
Barriers	Small PV modules are in short supply and therefore expensive. This is especially true for non-glass modules, which are needed for urban applications due to vandalism concerns. Sunlight levels cannot be accurately predicted for multiple locations, which results in some systems underperforming. This prevents installation in all desired locations.
PV technology	PV capacities of 1-150Wp are used. Non-glass is preferred, though presently in short supply and more expensive. Thin-film modules with good ambient light performance are ideal and should be used in the majority of applications. However, most systems use crystalline simply due to space constraints and cost.
Batteries	Nickel metal hydride, nickel cadmium for consumer sizes, lead acid for larger capacities (>10Ahr)
Crystalline modules	Used due to cost. Often packaged between fibreglass and a clear resin instead of glass and a frame. These modules are fragile with reduced life.
PV manufacturers	Very few crystalline manufacturers produce small modules themselves (<60Wp). Cells are typically supplied to third parties that produce small modules.

Huge opportunity in thin-film once appropriate cost and volume achieved

Figure 57

Opportunities for thin-film in small/medium-scale deployed designs

Volume must be available	Small modules are not produced at sufficient volumes to realise cost reduction. Automated production of 1-40Wp at the right cost could actualise the potential of the market.
Cost	PV can account for over 70% of the system cost. If the thin-film product has additional benefits at a similar cost it will be used.
Good solution design can boost already superior PV	In many solutions a great deal of the PV potential is wasted. Standard batteries need to be charged under conditions that PVs cannot provide. If the batteries and charging circuit are correctly designed they will increase the value of the solution using less PV
Compatibility is straight forward	Although the PV is often incorporated into the product, thin-film can replace the existing PV as long as it is similar in size. It would either have the same efficiency or slightly lower with better low light response.
A better solution	Less dependency on direct light allows mass deployment of solutions.
Large projects waiting for thin-film	There are a number of very large projects for which thin-film could be the enabling factor. For example, climate change scientists are keen to install a global network of monitors to predict extreme weather such as an El Niño and hurricanes.

Source: Author

Portable and consumer solutions: Shape of things to come

Products limited at present, not perform well; Thin-film can change this

Portable and consumer goods offer considerable potential for thin-film with high volumes and margins on offer and the absence of a global brand in PV. Meanwhile, most consumers are unfamiliar with the different variations of technology. Thin-film has a real opportunity to truly move the industry into the consumer-goods realm.

Effective solutions are rare at present. Products tend to use too little PV for cost reasons and the resulting performance is poor except in idea sunlight.

Figure 58

Portable and consumer sector summary

Typical applications	Calculators, watches, consumer battery chargers, chargers for mobile phone, PDA's laptops etc. Developing countries: From lighting and refrigeration in a simple home to radios and mobile phones to be carried by an individual.
Location	Everywhere. Value increases with distance from the mains grid.
Economic drivers	Additional functionality that the PV energy provides. In developing countries the problem of personal energy is simple: there is often no other means to charge a phone or portable device. Funding is not the greatest restriction, it is the PV.
Barriers	Poor functionality at present due to cost and size. Limited formats make product integration difficult or compromising. New technologies have limited life at present. User awareness of PV limits effectiveness. Exaggerated product marketing or inappropriate products for climate type have damaged reputations.
PV technology	Crystalline is still dominant, though only in the absence of alternatives. Flexible modules are highly desired but at present are limited in volume and expensive.
Crystalline modules	Small crystalline (5-40Wp) modules are disproportionately bulky and heavy. They are often produced by third-party assemblers using off-cut crystalline cells. Modules can be >US$20/Wp.
PV manufacturers	We have yet to see a manufacturer with volume that is appropriate for this market. UniSolar has come the closest with glass-free small modules, but then neglected the market in favour of grid-connect.

Figure 59

Basic design parameters

Where is the solution being used?	Geographically and locally. Strong diffuse sunlight regions are ideal. The sunlight resources in a high latitude city are drastically different from an open area nearer the equator.
How is the user operating the product?	The simplest method is to lay the PV on the ground. This is not ideal but it does allow a degree of sunlight energy prediction. If the PV product is wearable and constantly changing orientation and angle the generating potential is significantly decreased.
What is being charged?	The duration of the load/daily energy requirement is often unknown. For all solutions the user plays a crucial role in the effectiveness of the product.

Source: Author

Figure 60

Opportunities for thin-film in consumer products

Volume must be available	Small modules are not produced at sufficient volumes to result in cost reduction. Automated production of 1-40Wp at the right cost could see the market's potential realised.
Cost	PV can account for over 70% of the system cost. If the thin-film product has additional benefits at a similar cost it will be used.
Good solution design can boost already superior PV	In many solutions a great deal of the PV potential is wasted. Standard batteries need to be charged under conditions that PV cannot provide. If the batteries and charging circuit are correctly designed they will increase the value of the solution using less PV
Compatibility is straight forward	Although the PV is often incorporated into the product, thin-film can replace the existing PV as long as it is similar in size. Either it is the same efficiency or slightly lower with better low light response.
A better solution	Less dependency on direct light allows mass deployment of solutions.
Advancing battery technology enables more PV solutions	Battery technology is advancing significantly, though the ability to charge the battery during everyday activities carries an ever increasing commercial value. Batteries are becoming more capable of trickle charging and can withstand high temperatures.
Large projects waiting for thin-film	**Lighting**: The IFC states that independent estimates indicate worldwide spending on fuel-based lighting in developing countries is US$38bn/year. Kerosene lamps account for a significant portion of this expenditure. Not only does the use of Kerosene have health and safety issues, as previously mentioned it emits over 2.5kg of CO_2 per litre burnt. PV solutions replacing or preventing the purchase of kerosene are eligible for carbon credits. **Mobile phone charging** could be a US$50bn market. The major handset manufacturers have all identified over 1.5 billion people in the developing world as potential customers over the next five years. China, India, South America and especially Africa represent the major areas where a phone has significantly more value than in their present industrialised markets.

Source: Author

Appendix 1: Thin-film manufacturers

Many of the large producers are involved with more than one technology; advancements in existing, emerging and novel technologies involve hundreds of universities, agencies and research centres, many of which operate in collaboration with the PV industry. There is also development in parallel industries such as organic LED and flat screen TVs.

Notable thin-film manufacturers

Company	Technology	Stock Code	Status	Comments
AMI	a-Si	-		
Bangkok Solar	a-Si	-		
BP Solar	a-Si	45936Z US		Bought Solarex in 1999 and in top 5 manufacturers until mid-2000s.
Brilliant	a-Si	-		
Canon	a-Si	7751 JT		
CMC	a-Si	CMC US		
Dunasolar	a-Si	-		
Energy PV	a-Si	-		
Ersol	a-Si	ES6 GR		
Free Energy Europe	a-Si	-		
Fuji	a-Si	FUJI US		
GET	a-Si	3519 TT		
Helio Grid	a-Si	ICPR US		
ICP Solar Technologies	a-Si	-		Created in 1988 and strong in the consumer products market.
Kanto Sanyo	a-Si	-		
MH1	a-Si	-		
Mosen Baer	a-Si	MBI IN		
MWOE Solar	a-Si	-		
Nano PV	a-Si	-		
Nanowin Tech	a-Si	-		
OptiSolar	a-Si	-		
Sharp	a-Si	6753 JT		Second-biggest manufacturer in 2007, previously the largest.
Shenzhen Topray Solar	a-Si	002218 CH		
Signet Solar	a-Si	-		
Sinonar	a-Si	8036 TT		
Solar Cells	a-Si	-		
Solar Morph	a-Si	-		
Solar Plus	a-Si	-		
Soltech	a-Si	-		
SunFirm	a-Si	-		
Suntech Power	a-Si	STP US		
T.J. Solar	a-Si	-		
Terra Solar	a-Si	-		
Tianjin Jinneng Solar Cell	a-Si	-		
Iowa Thin-film (Power Film)	a-Si (flexible)	-	Ramping up production from pilot level.	
VHF Technologies (Flexcell)	a-Si (flexible)	-	Ramping up production from pilot level	Part-owned by Q-Cells, the biggest crystalline cell manufacturer last year.
EPOD	a-Si 2 jnc	-		
EPV	a-Si 2 jnc	25675Z US		
UniSolar	a-Si 3 jnc (flexible)	ENER US	Aiming for >500MW within two years.	
Kaneka	a-Si/mc-Si	4118 JP	One of the leading a-Si producers.	
Sharp	a-Si/mc-Si	-		
Xunlight	a-Si/mc-Si	-		
Antec Solar	CdTe	-		
Ascentool	CdTe	-		
AVA Solar	CdTe	-		
Canrom	CdTe	-		
Clyxco	CdTe	-		
First Solar	CdTe	FSLR US	Aiming for >1GWp by 2010.	First CdTe commercial producer.

Continued on the next page

Notable thin-film manufacturers (cont'd)

Company	Technology	Stock Code	Status	Comments
Nuvo Solar Energy	CdTe	-		
Primestar Solar	CdTe	-		
Solar Fields	CdTe	-		
Zia Watt Solar	CdTe	-		
Aleo Solar	CIS	AS1 GR		
Ascent Solar	CIS	ASTI US		
Avancis	CIS	-		
CIS Solartechnik GmbH	CIS	-		
Dow Chemicals	CIS	DOW US		
EPV	CIS	-		
Global Solar	CIS	708192Z US	Ramping up to >100MWp.	First 'flexible' CIGS products.
Heliovolt	CIS	-		
Honda	CIS	7267 JT		
ISET	CIS	-		
ITN/ES	CIS	-		
johanna solar technologies	CIS	-		
Light Solar	CIS	-		
Odersun	CIS	-		
RESI	CIS	-		
Scheuten Solar	CIS	-		
Showa Shell	CIS	5002 JT		
Solisbro	CIS	-		
SoloPower	CIS	-		
Solyndra	CIS	-		
Stion	CIS	-		
Sulfurcell	CIS	-		
Wurth Solar	CIS	-		
Daystar	CIS (flexible)	DSTI US		
Global Solar	CIS (flexible)	-		
Miasolé	CIS (flexible)	-	Pre-pilot production.	Huge financing for >5 years and still no product.
Nanosolar	CIS (flexible)	-	Pre-pilot production.	Huge financing for >5 years and still no product.
Solarion	CIS (flexible)	-		
CSG Solar AG	CSG	-		
Dyesol	DSSC	-	Not in production.	Aiming to supply materials for DSSC and OPV.
G24 Innovations	DSSC	-	Pre-pilot production.	First DSSC commercial production attempt.
Greatcell Solar	DSSC	-		
Konarka	DSSC	-	Never in production.	Now moved to OPV but well known for DSSC.
Peccel	DSSC	-		
Prism Solar	Holographics crystalline	6764 JP	Proof of concept only.	Unlikely to succeed commercially.
Sanyo	Non-standard crystalline	SPWR US		Eighth-largest manufacturer in 2007.
SunPower	Non-standard crystalline	ESLR US		
Evergreen Solar	Ribbon Silicon	GE US		
GE Energy	Ribbon Silicon	-		
RWE Schott Solar	Ribbon Silicon	-		One of Europe's biggest manufacturers.
Origin Solar	Sliver crystalline	-	Proof of concept only.	Unlikely to succeed commercially.
Kyosemi Corporation	Spherical crystalline	-	Returned to proof of concept.	Original product failed expectations. Very challenging.
Spheral Solar Power	Spherical crystalline	AMAT US	Proof of concept only.	
Applied Materials	Thin-Si	-		Promoting turn key a-Si solutions.
CSG Solar	Thin-Si	-	Pilot production.	
Innovalight	Thin-Si	-		
MV Systems	Thin-Si	-		
Nanogram	Thin-Si	-		
New Solar Ventures	Thin-Si	-		
Proto Flex	Thin-Si	-		
Signet Solar	Thin-Si	-		
Solexant	Thin-Si	-		
Soltaix	Thin-Si	-		
XsunX	Thin-Si	-		

Source: CLSA Asia-Pacific Markets

Appendix 2: Technology R&D

There are hundreds of R&D issues; these are some of the immediate challenges

Each of the major technologies face hundreds of research issues. The list below is representative of the immediate challenges that must be addressed in order for commercial volumes to significantly increase over the next five years.

TFSi

- Processes and equipment for low-cost, large area deposition
- Improved understanding of interface and material properties, and of the fundamental limits for TFSi-based devices
- Development of high-quality low cost TCOs

CIGSS

The fundamentals of CIGS need better understanding

- Deeper understanding of the fundamental physics of these devices
- Improvement of the throughput, yield and degree of standardisation of production equipment
- Higher module efficiencies
- Prevention of moisture ingress for flexible CIGS modules
- Alternative/modified material combinations
- Alternative approaches to processing like roll-to-roll coating

CdTe

- Control of uniformity over large area
- Improved back-contacting for enhanced yield and throughput
- Concepts for higher efficiency
- New device concepts for thinner CdTe layers
- Standardization of equipment for deposition of the absorber layer
- Enhanced fundamental knowledge of materials and interfaces

OPV and DSSC

A lot of media attention but not ready for market yet

- Improvement of cell and module efficiencies and stability to the level needed for first commercial application
- Encapsulation materials and processes specific to this family of cell technologies
- Product concepts and first generation manufacturing technologies

Crystalline

The scale and diversity of R&D is immense

Given the scale and diversity of research and development into improving crystalline module production, the list below is by no means definitive. It does however give an indication of the potential for vast cost savings and production increases.

Each of these major development areas will improve product commercial performance

Major R&D areas
Improved electrical modelling of cells and modules
Improved mechanical modelling of materials
Improved prediction of reliability by accelerated life testing
Lower cost silicon feedstock preparation
Lower embodied energy in feedstock preparation
Reusable crucibles (with low impurity)
Reduced waste of polysilicon crystallisation
Improve crystal growth – higher potential efficiencies
Improved defect characterisation in silicon
Improve the efficiency of 'dirty silicon'
Reduce waste from polysilicon sawing (and improve recycling)
Reduce polysilicon cut-off waste (and improve recycling)
Thinner cells – to improve g/Wp factor
Increase cell efficiencies (+1% = >5% cost/Wp saving)
Improve material handling (to reduce breakages)
Optimise cost and transmissivity of front glass (to increase efficiency)
Reduce cost of module glass, polymer and frame
Reduce embodied energy of module glass, polymer and frame
Improve automated cell handling for module assembly
Increase power density of modules
Encapsulation material cost reduction
Encapsulation materials more flexible and durable
Lower cost cell interconnection materials and methods
Utilisation of conductive adhesives (for solder-free solutions)
Improved cell connection grids (reduced shading area)
Refine cell back-contact effectiveness and production efficiency
Develop alternatives to scarce materials (such as silver)
Avoidance of hazardous materials in process
Recycle chemicals used in production

Source: Author

Appendix 3: Off-grid applications

The system is a battery charger, with numerous applications

There are multiple applications within each of these sectors

There are hundreds of uses for off-grid PV, ie, remote power supply. The list below offers an example of the major sectors and applications.

Uses for off-grid PV

Industrialised world	
Industrial infrastructure	Telecom repeater stations, oil & gas protection, water desalination, etc
Outdoor	Warning lights, irrigation, electric fencing, emergency phones/medical, pest control, location devices, satellite phones, etc
Monitoring	Air: greenhouse gasses, pollution, temperature, humidity, wind speed Environment: noise levels, traffic volumes Water: Rainfall, leakage, flow rates, levels
Advertising	Street "furniture"; bus shelters, billboards
Transport	Traffic control (fixed and temporary), roadside generation, roadside information. Rail infrastructure, waterways
Military	Soldier equipment: communications, location tags, GPS, IT equipment, night vision, lighting
Consumer/lifestyle	Calculators, phone & PDA charging, watches, lighting, personal security
Marine	Buoy lights, lifebuoy lights, sensors, location devices
Security	Security barriers, perimeter security, surveillance, motion sensors, lighting
Leisure	Caravans, boating, holiday homes, camping: refrigeration, security, lighting, insect repellent, device charging, etc
Indoor	Smoke alarms, price tags, security tags, gas sensors, door locks, appliance standby consumption
Developing world	
Rural electrification	Electric fences, security, irrigation, lighting (community, medical and educational centres)
Communications	Telecoms repeaters, internet access, international phones
Medical	Portable & fixed refrigeration (vaccines, blood, organs), lighting, monitors, aids medication timers, water purification
Domestic	Lighting, refrigeration, water purification
Media & IT	School & college computers, TV, radio, educational films, etc
Transport infrastructure	(Road & rail) Lighting, traffic control, warning signs, monitoring
Personal	Phone chargers, battery chargers, water purification
Commercial	Amenity lighting, security, monitoring, advertising
Container energy systems	Industrial, commercial, infrastructure, etc
Emergency response	
Medical	Vaccine refrigeration, lighting, personal alarms, monitoring equipment, water purification
Shelter	Tent lighting, location devices, phone chargers
Communications	Satellite phones, internet access, camera charging

Source: Author

Appendix 4: Predicting energy generation

On and off-grid systems utilise sunlight potential differently

Grid-connected and off-grid systems use different methods to estimate energy generation for a system at a particular location since grid-connected systems are designed for maximum annual energy generation while off-grid ones are designed to operate under minimal light conditions, ie, winter.

Grid-connect systems and annual insolation

Grid-connect system generation is calculated using a kWh/m²/year figure, which describes the average intensity of sunlight for that location over a year. These values are published by a number of organisations including NASA and regional environmental bodies.

Off-grid systems and sun hours

Off-grid systems need to operate through the worst annual conditions

Off-grid systems are designed to operate in the worst sunlight conditions of the year. To assess the sunlight energy at a particular location over a day, 'Sun Hours' are calculated. 'Full sun' for one hour is a sun hour. Full Sun is 1000W/ m² (as used in standard test conditions) and is the value at which PV technology is rated (Wp) and produces maximum output. This term refers to solar insolation, which is used to standardise the quoted performance of PV technology, but is not a specification of real life performance (just as the Ahr rating of a battery is not a specification of its performance.)

As a guide to full sun conditions, this will be with the sun high in the sky - locations near the equator or summer season - no cloud cover and the PV directly facing the sun without any shading.

A sun hour is a cumulative figure. For example, on the equator with a horizontal PV module, from 6am (sunrise) to 7am the PV may be exposed to 0.25 sun; from 7am to 8am intensity may be 0.5 sun; 8am to 9am may be 0.75 sun. This would result in the PV being exposed to 1.5 sun hours between 6am and 9am.

Sun hours are particularly important for portable and consumer goods. These products are sold over a wide geographical area, though are typically designed to work in areas with strong sun - high sun hour locations. The performance of the product will vary throughout the year as sunlight changes.

Example sun hour figures against daylight hours

Example sun hours and locations

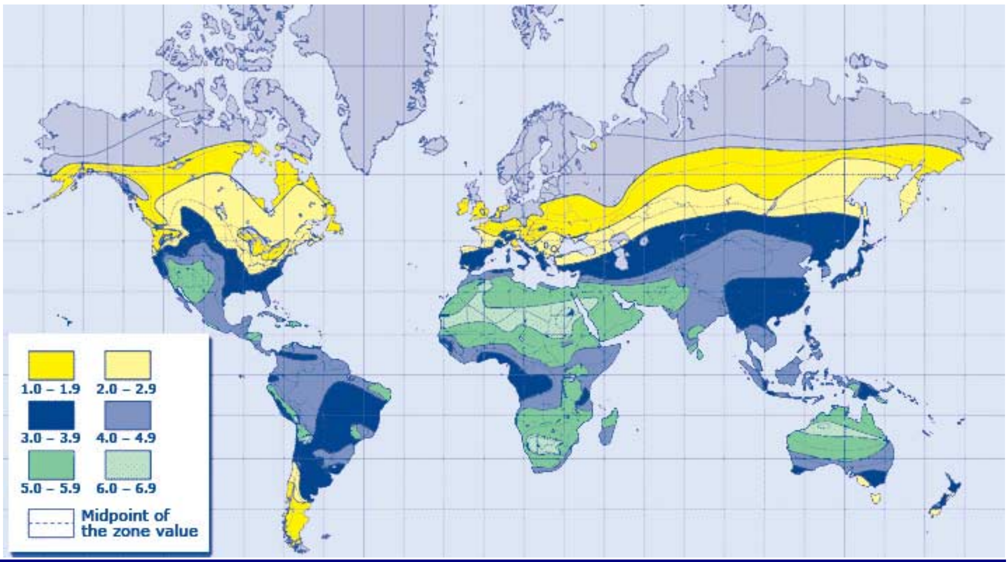
Location	Sun Hours		Daylight hours	
	Peak summer month	Lowest winter month	Peak summer month	Lowest winter month
Singapore	5.8 (Feb)	4 (Dec)	12	12
Delhi	7.5 (May)	3.5 (Dec)	13.5	10.3
Hong Kong	5 (Jul)	3 (Feb)	13.5	11
Beijing	6.5 (Jun)	2.5 (Dec)	15	9.5
London	6 (Jun)	<1 (Dec)	17	7.5
New York	5.5 (Jun)	1.5 (Dec)	15	9.5
Tokyo	6 (Jun)	2.5 (Dec)	15	9.5

Source: NASA, Author

The world insolation map below shows minimum sun hours across the globe.

Minimum sun resource data is required to size off-grid systems

World Insolation (sun hours) Map



Note: Minimum (winter) average sun hours shown. Local climate and/or environment can vary significantly. The further from the equator, the greater the increase in sun hours from winter to summer months. For example, UK daylight hours range from <8 in winter to >16 in summer; Sun hours range from <1 in winter to >6 in the summer. Source: NASA

Appendix 5: Glossary of terms

The PV industry seems to accumulate new acronyms every week!

Glossary of terms for this report

a-Si	Amorphous silicon	Thin-film PV.
BIPV	Building Integrated Photovoltaics	PV forms part of the building fabric, not simply bolted on.
BOM	Bill of materials	The total list of materials required for an installation.
BOS	Balance of system	The components other than the PV.
CdTe	Cadmium Telluride	Thin-film PV.
CIGS	Copper Indium Gallium Selenium	Thin-film PV.
CIS	Copper Indium Selenium	Thin-film PV.
CO_2	Carbon Dioxide	Used to represent greenhouse gasses emitted from burning fuels, etc.
CSG	Crystalline Silicon on Glass	Produced by CSG Solar AG.
DNO	Distribution Network Operator	Owner of the cables running to a building.
EPIA	European Photovoltaic Industry Association	
GGL	Glass-Glass Laminate	Crystalline cells laminated between two sheets of glass.
HIT	Heterojunction with Intrinsic Thin layer	Sanyo cells using a-Si and crystalline wafers.
IEA	International Energy Agency	
III-V cells	Cells using elements from columns 3 and 5 of the periodic table	Space and concentrator applications.
ISES	International Solar Energy Society	
kWh	Kilo Watt-hour (1000 Watts)	A unit of mains electricity. 1kW for one hour or equivalent.
LSBIPV	Large Scale Building Integrated PV	
MPPT	Maximum Power Point Tracking	Used in off-grid system charge controllers to optimise PV energy.
NOCT	Normal Operating Cell Temperature	
PDA	Personal Digital Assistant	Blackberry, et al.
PV	Photovoltaics	Direct conversion of light into electricity.
RDA	Regional Development Agency	
SOC	State of Charge	With reference to batteries.
STC	Standard Test Conditions	1000W/m² of specific light; 25°C; Air Mass 1.5 (represents Earth's atmosphere).
UV	Ultra-violet	Light.
Wp	Watts peak	The rated power of a PV module under standard test conditions.

Source: Author

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